NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

National Environmental Satellite, Data, and Information Service

Creating Climate Data Records from NOAA Operational Satellites

White Paper

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Executive Summary

The importance of understanding and predicting climate variation and change has escalated significantly in the last decade. To integrate federal research on global climate change, President George W. Bush announced in February, 2002 the formation of a new management structure, the Climate Change Science Program (CCSP).[1] The National Academies' National Research Council (NRC) has recommended several research priorities for climate research[2] and the CCSP[3] drafted a strategic plan, which was reviewed by the NRC. CCSP issued a final plan in July, 2003.[4]

In response to these national initiatives in climate science, the NOAA National Environmental Satellite Data and Information Service (NESDIS) will develop a NOAA Plan for Creating Climate Data Records from Operational Satellites to provide a framework for the use of climate data from existing and new instruments aboard NOAA satellites, including instruments on the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The goal of the plan is to ensure that satellite climate data are processed, archived, and distributed to users in a manner that is scientifically defensible for monitoring, diagnosing, understanding, predicting, modeling, and assessing climate variation and change.

The NOAA mission is to understand and predict changes in the Earth's environment and conserve and manage coastal and marine resources to meet the Nation's economic, social and environmental needs. NOAA has statutory responsibility for long-term archiving of the nation's environmental data[5] and has recently integrated several data management functions into a Scientific Data Stewardship initiative. These functions include careful monitoring of observing system performance for long-term applications, the generation of authoritative long-term records from multiple observing platforms, and the proper archival of and timely access to data and metadata.

NESDIS maintains the world's largest archive of climate-related data and information spanning the ice age to the space age. NESDIS also operates the Nation's operational satellite observing system and is developing and implementing the U.S. Climate Reference Network (CRN). Data and information from NOAA space-based and ground-based observing systems are used along with other climate-related NOAA and non-NOAA observing system data to construct long-term records regarding local, regional, national, and global climate variability and change. Within NESDIS are three large data centers that archive and provide access to climate, ocean, and geophysical data. The National Climatic Data Center (NCDC) in Asheville, North Carolina is the largest archive of weather data in the world.

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[1] These research efforts include the activities under the previously established U.S. Global Change Research Program (USGCRP) and the Climate Change Research Initiative (CCRI).

[2] *Climate Change Science: Analysis of Some Key Questions"*, NRC, 2001.

[3] The NOAA Climate Program manages new and existing climate activities that cut across all NOAA line offices, and is a key component in implementation of the national CCSP, acting as the interface between national and interagency planning efforts.

[4] *Strategic Plan for the Science Change Science Program*, Final Report, July, 2003.

[5] *New Priorities for the 21st Century, NOAA's Strategic Plan for FY2003-2008 and Beyond* March, 2003, specifically outlines NOAA's roles and responsibilities for providing quality climate data.

Climate research is generally based on data collected for other purposes, primarily for weather prediction. To make these data useful for climate studies, it is usually necessary to analyze and process the basic observational record to create a *Climate Data Record* (CDR)[6]. A CDR is a series of observations over time that measures variables believed to be associated with climate variation and change. These changes may be small and occur over long time periods (seasonal, interannual, and decadal to centennial) compared to the short-term changes that are monitored for weather forecasting. Thus, it is usually necessary to construct a CDR from data that span long time scales and sometimes from multiple data sources. Scientists must characterize and quantify the sensor, spatial and temporal errors of these diverse and frequently large data sets in order to produce a sufficiently accurate time series for studying trends in climate variability and change.

Climate: Long-term averages of weather conditions. Typically, 30 years of data have been used to form the climatological means.

Climate Variability: Variations from long-term average weather conditions for time periods of a month or more.

Climate Change: Changes in the long-term averages of weather conditions, e.g., global warming, onset of ice ages.

The NOAA/NESDIS operational satellite data program currently collects, receives, produces, distributes, and archives data about climate, including the climate satellite products shown in the box. Many of these data are processed in response to specific requests from the scientific community who need long-time series climate records. In some cases, the raw data and metadata are provided to external investigators such as those in academia, at other U.S. agencies, or those involved in international projects, who produce the climate data records. NESDIS scientists also produce a number of climate products, either in-house or in collaboration with NASA. Examples of climate data records which have been developed from operational satellite observations are shown in Table ES-1.

Current NOAA Satellite Products

- **Atmosphere**
  - Temperature soundings
  - Moisture soundings
  - Winds
  - Clouds
  - Aerosols
  - Earth Radiation Budget
  - Precipitation
  - Ozone
- **Ocean**
  - Surface temperature
  - Ice cover
  - Surface winds
  - Color
  - Sea level
- **Land**
  - Vegetation condition
  - Snow Cover
  - Surface Temperature

Using existing satellite data to produce long-climate records has shown that adapting observations designed for weather prediction to climate issues in an *ad hoc* way is not sufficient to produce reliable findings and to draw reasonable conclusions about climate change. NOAA recognizes that the development of quality climate data records is key and that a program focus on the development, retention, and distribution of climate data records will be necessary to meet the needs of the science community.

[6] Data records that are used for real-time applications (for example, weather forecasting or current assessments) are similarly termed *Environmental Data Records* (EDR)

Table ES-1. Examples of Climate Data Records Based on Operational Satellite Observations

Climate Product	Satellite/Instrument	Produced by	Since
Earth Radiation Budget (ERB) Outgoing long-wave radiation (OLR) Absorbed solar radiation (ASR)	POES/AVHRR	NESDIS	1978
Ozone	POES/SBUV/2 & POES/ATOVS/HIRS	NESDIS/NASA	1985
Blended Sea Surface Temperature (SST)	POES/AVHRR	NESDIS/NWS	1981
DMSP SSM/I Climate Products (rainfall, rain frequency, snow cover, sea ice cover, clouds, water vapor, and oceanic wind speed)	DMSP SSM/I	NESDIS	1987
Vegetation (NDVI and drought index)	POES/AVHRR		1982
Atmospheric Temperature	POES/MSU	Univ. of Alabama	1979
Snow Cover	POES/AVHRR, GOES, Meteosat, GMS Visible imagery, DMSP/SSM/I	Rutgers Univ. Climate Laboratory	1966
Clouds	POES/AVHRR; GOES, Meteosat, and GMS Visible IR imagery	WCRP/International Satellite Cloud Climatology Project	1983
Precipitation	POES/AVHRR; GOES; Meteosat and GMS Visible IR imagery, DMSP SSM/I	WCRP/Global Precipitation Climatology Project	1986

Efforts to use the operational environmental satellite observations over the past decade or more have resulted in a set of recommendations from researchers that have recently been formalized by the climate community into satellite climate observing principles. Six of those principles are essential topics for discussion and recommendations of this report:

- Development and operational production of priority climate products should be ensured.
- Systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained.
- Continuing use of still-functioning baseline instruments on otherwise de-commissioned satellites should be considered.
- The need for complementary in-situ baseline observations for satellite measurements should be appropriately recognized.
- Network performance monitoring systems to identify both random errors and time-dependent biases in satellite observations should be established.
- Multiple observing and analysis techniques for critical climate data records should be used.

Conceptual Framework

For discussion purposes, a framework for accommodating the requirements and lessons learned outlined above and that is consistent with the CCSP strategic plan for monitoring and observing the climate system is presented. The framework has five objectives: 1) develop real-time monitoring of all satellite observing systems, 2) generate CDRs in near real-time, 3) process large volumes of satellite data extending up to decades in length to account for systematic errors and to eliminate artifacts, 4) conduct research by analyzing data sets to uncover climate trends, and 5) provide archives of both raw data records (RDRs) and CDRs, and facilitate distribution of CDRs to the research community. Each phase of this end-to-end system will require collaboration with climate data science teams, input from climate data users, and should leverage knowledge and resources from other climate data programs and organizations. The framework is depicted in Figure ES-1.

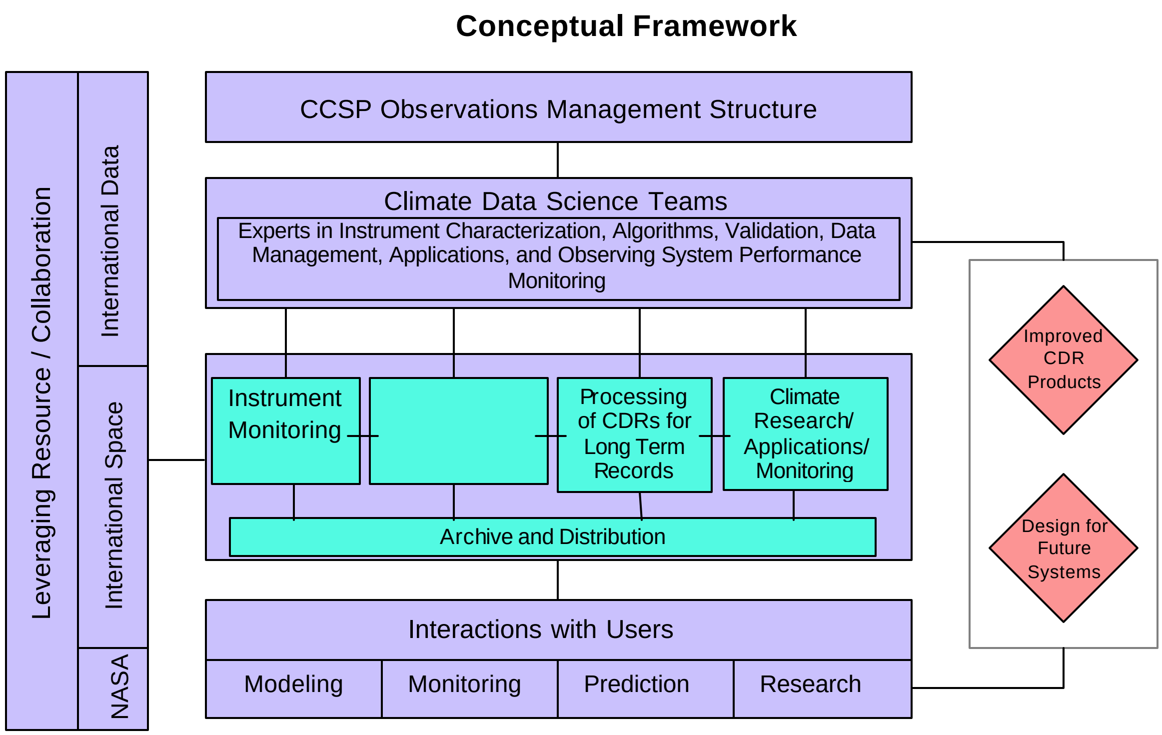

Figure ES-1. Conceptual Framework for Creating Climate Data Records

Observing System Performance Monitoring Understanding the effects of the observing system on the data measurements in real-time will provide data of known quality, and for which temporal and spatial biases can be minimized. Observing factors affecting the data quality include the following:

- Biases inherent in the observing system
- Changes in instruments
- Satellite orbital drift
- System calibration
- Sensor degradation in space
- Satellite to satellite discontinuities

- Satellite or instrument system malfunction

Near Real-Time CDR Generation Climate researchers need satellite data on an ongoing basis for prediction of climate variability, such as the El Niño-Southern Oscillation, extreme storm events, excessive rainfall, or drought. Therefore the capability to provide routine observations and generate CDRs in near real-time is needed.

In addition, scientists need to develop data sets that can be compared with or added to the historic record for monitoring long-term climate changes. As data are received, scientists at NOAA will automatically update historical climate data bases to maintain a global climate perspective in near real-time.

Converting the raw data records, sensor data records, and EDRs, when applicable, to produce CDRs and science products will be a major challenge that will require leveraging the knowledge of NOAA and NASA researchers, and other members of the scientific community to develop the algorithms. These efforts will involve the following:

- Calibration, inter-calibration and characterization of satellite instruments
- Development of processing algorithms
- Detection and elimination of systematic errors in the data set
- Generation of stable climatic time series
- Validation of data products
- Analysis of data

Processing Periodic processing of data sets will be necessary to incorporate new information, new instruments, and improved algorithms.

Periodic processing of the long-term data record may be called for when:

- *An improved algorithm is developed*
  Data will be reprocessed to accommodate the latest scientific findings into the data products. As scientific research improves our understanding of the earth's physical processes, existing algorithms will be refined or replaced with new algorithms.

- *New information on the in-flight behavior of an instrument is obtained*
  Recalibration of measurements may be performed as a result of analysis of instrument behavior.

- *An error is discovered in a processing system*
  A coding or other software error may be discovered in the processing system. This type of error may not be detected in an EDR, but analysis and comparison with other data sets may reveal an error at the CDR level.

Research and Application Another component of the framework involves a research activity, as opposed to the "housekeeping" responsibility of processing data sets. In addition to developing CDR algorithms, climate researchers, working with the long-term data record will continue to make contributions to climate change and variation research by analyzing data sets to uncover trends. Activities will include the following:

- Development of climate quality algorithms for creating CDRs.

- Analysis of time series to detect trends that may be emerging from the record, and comparing the results to results of other researchers.
- Joint studies with the climate research community to advance the use of satellite data for climate applications.
- Production of periodic assessments for decision makers, other climate researchers, and the public.

Data Archive and Access An operational climate data service must ensure that all climate data are preserved and made available to users. In addition to the climate data; metadata; production software source code; documentation on the data, meta data and data formats; ancillary data; calibration/validation information; and QA information will also be archived. Regular back-up of data and the capability to migrate any or all of this information to new media are also important.

The primary goal of the NESDIS plan for the generation of climate data records will be to support the user. Therefore, a critical objective is to provide free and open sharing and exchange of climate related data and products. Services will include availability of data in near real-time, and access to both raw radiances and NOAA data products. Community consensus algorithms and techniques will be sought to accomplish these goals. Standards will be developed for the data and media format to be supported for data distribution.

Discussion Issues

To ensure that CDRs are both accessible and useful to climate researchers and decision makers, and to promote science community participation and consensus, NESDIS is seeking advice from the National Academies on a number of issues prior to the development of a plan for creating climate data records from NOAA satellites:

- **Science oversight and participation by external community**
  Examples of functions that could be carried out in this way include algorithm development, generation of CDRs (for the smaller data sets), validation campaigns, research with the data sets, and the evaluation of the data in climate models for other applications.

  Issues: What approach should NOAA consider for obtaining science guidance and oversight for its end-to-end CDR program? What scientific criteria should be used to decide whether a function should be performed in-house or externally?

- **NOAA/NASA relationship**
  NOAA and NASA have a history of cooperative activities related to CDR generation, including the NOAA/NASA Pathfinder program, the joint NOAA and NASA support of the development of data sets for NOAA's Climate Change Data and Detection project, NOAA scientist participation on NASA science teams that produce CDRs, and the NOAA/NASA cooperation on the generation of a long-term ozone data.

  Issues: What are some realistic options for engaging NASA in an end-to-end system for generating CDRs from the operational satellites?

- **Obtaining feedback from users**
  It is extremely important that NOAA obtain feedback from the user community on the

utility of the CDRs in various climate applications – climate monitoring and diagnosis, seasonal to interannual climate prediction, decadal scale climate modeling, climate research, and other governmental and private sector applications.

Issues: What are the optimal mechanisms for entraining the user community in the use, test, and evaluation of CDRs and for obtaining feedback?

- **Participation in international data projects**
  Some of the widely used satellite climate data sets have been produced as part of international programs. To the extent that these programs use operational satellite data and are intended to provide a sustained, long-term record, it seems appropriate for NOAA to actively participate in such programs.

  Issues: What should be the role of NOAA in international data projects? What functions should NOAA perform?

- **Algorithm selection**
  For operational programs, algorithms are selected in a variety of ways. NOAA's satellite EDRs, for example are selected via in-house Product Oversight Panels. NESDIS will explore similar or other viable approaches for selecting algorithms.

  Issues: What are some viable approaches for algorithm selection? Once an algorithm is implemented, what procedures should be used to determine when the algorithm should be updated or replaced? How should replacement algorithms be selected?

Summary

NOAA's vision is that through the establishment and execution of an end-to-end system for CDRs, more confident conclusions may be drawn regarding climate variability and change, and that this improvement will benefit policy makers and the public at large. By establishing a programmatic framework to properly address issues surrounding climate data records, NOAA will ensure the quality, usefulness, and accessibility of the data for current and future generations.

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1 Introduction

As much as $4 trillion of the nation's $10 trillion economy is affected by weather and climate events each year. Industries such as transportation, energy, and agriculture rely on accurate climate and weather information and predictions. Improved seasonal to interannual climate forecasts have become increasingly important to predict periods of drought or intense storm activity such as hurricanes - occurrences of which can significantly affect the economy.

> **Climate**: Long-term averages of weather conditions. Typically, 30 years of data have been used to form the climatological means.
>
> **Climate Variability**: Variations from long-term average weather conditions for time periods of a month or more.
>
> **Climate Change**: Changes in the long-term averages of weather conditions, e.g. global warming, onset of ice ages.

The importance of understanding and predicting climate variation and change has escalated in the last decade. In February 2002, President George W. Bush announced the formation of a new management structure, the Climate Change Science Program (CCSP), which integrates federal research on climate and global change. The CCSP is sponsored by thirteen federal agencies and overseen by the Office of Science and Technology Policy, the Council on Environmental Quality, the National Economic Council and the Office of Management and Budget. The CCSP was formed to coordinate and direct the U.S. research efforts in the areas of climate and global change. These research efforts include the activities under the previously established U.S. Global Change Research Program (USGCRP) and the Climate Change Research Initiative (CCRI) to reduce significant uncertainties in climate science, improve global climate observing systems, and develop resources to support policymaking and resource management. The CCSP has developed a strategic plan, which was reviewed in draft form by the National Academies' National Research Council (NRC).

Several reports have documented weaknesses in current programs and gaps in data that impact the usefulness of climate records. An NRC report, "Climate Change Science: An Analysis of Some Key Questions", recommended research priorities to help reduce uncertainties in climate science. One key recommendation was to "ensure the existence of a long-term monitoring system that provides a more definitive observational foundation to evaluate decadal-to century-scale changes."

The National Oceanic and Atmospheric Administration (NOAA) has demonstrated strong management support for an enhanced climate program. Recently NOAA established a NOAA Climate Program which cuts across all of NOAA line offices and has established a Scientific Data Stewardship (SDS) Initiative for FY 2005. Under the SDS Initiative, the National Environmental Satellite, Data, and Information Service (NESDIS) within NOAA will monitor observing system performance for long-term applications and generate authoritative long-term records. This white paper, "Creating Climate Data Records from NOAA Operational Satellites", is another component of NESDIS' response to the new national climate initiative.

The white paper identifies the need to establish an end-to-end system for the use of current and future instruments aboard NOAA satellites for climate applications. NOAA operates two environmental satellite programs, the Geostationary and the Polar-orbiting. Due to the evolution of polar satellites in the next five to ten years, the program would focus on polar satellites, instruments, and climate data. During this time period, National Aeronautics and Space Administration's (NASA) sustained climate observations are transitioning to NOAA. The goal of the program is to ensure that satellite climate data are processed, archived, and distributed to users in a manner that is scientifically defensible for monitoring, diagnosing, understanding, predicting, modeling, and assessing climate variation and change.

1.1 Background

NOAA's mission is to understand and predict changes in the Earth's environment and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs. NOAA observing systems measure and monitor the Earth every day. NOAA gathers and manages global data and data bases about the oceans, Earth, air, space, and sun and their interactions to describe and predict the state of the physical environment. The data are used in weather warnings and prediction; oceanographic forecasts; climate monitoring, assessments, and prediction; detecting environmental hazards; and environmental research.

The NOAA Climate Program manages new and existing climate activities that cut across all NOAA line offices. Climate research and products are developed to support national, regional, and local users both within and external to NOAA. This program is also a key component in implementing the CCSP. The NOAA Climate Program acts as the interface between both national interagency and intra-agency planning efforts. NOAA's activities, which focus both on near-term deliverables and longer research, will be integrated and managed for performance by the Climate Program.

NESDIS, an organization in NOAA, maintains the world's largest archive of climate-related data and information spanning the ice age to the space age. NESDIS operates the nation's operational satellite observing system, which provides essential data for understanding climate variability and change. NESDIS is also currently developing and implementing the U.S. Climate Reference Network (USCRN) to provide reference quality in-situ data for temperature and precipitation monitoring. Data and information from these observing systems are used along with other climate-related NOAA and non-NOAA observing system data to construct long-term records regarding local, regional, national, and global climate variability and change.

Currently both national and global data sets are used by both government and the private sector to minimize the risks of climate variability and weather extremes such as hurricanes, tornados, heavy precipitation, temperature extremes, and drought. The data sets help to describe the climate of the United States and other countries and allow for trends and anomalies of weather and climate to be documented. Climate data, currently archived at the National Climatic Data Center (NCDC), have been used in a variety of applications including the following:

- Agriculture
- Air quality
- Construction
- Education
- Energy
- Engineering
- Forestry
- Health
- Insurance
- Landscape design
- Livestock management
- Manufacturing
- Recreation and tourism
- Retailing
- Transportation
- Water resources management

The science community uses climate data in the following ways:

- Diagnosing climate variations (e.g., the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO)
- Initializing and validating seasonal to interannual climate forecasts
- Identifying boundary conditions and validating climate change models
- Monitoring long-term climate
- Researching climate

Figure 1-1 was produced from NOAA polar-orbiting satellites. The figure depicts a worldwide snapshot of drought-related severe vegetation stress, which is noted in red. Effects from the weather were felt in the United States, along with areas such as Africa, southeastern Europe, and central Asia. The dry and hot weather led to crop losses, pasture degradation, and intensive wildfires.

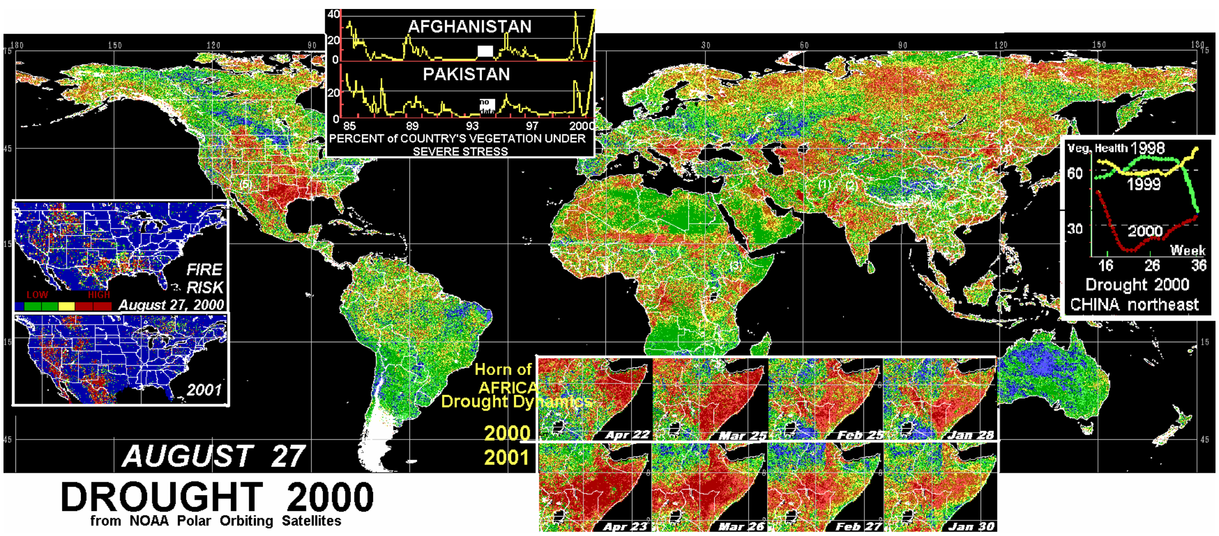

Figure 1-1. World Droughts in the New Millennium from AVHRR-Based Vegetation Health Indices

1.2 Mission and Goals

This white paper describes an approach for the exploitation of data for climate applications from current and future polar instruments, including those on the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The first NPOESS launch, scheduled for 2009, will merge existing polar-orbiting satellite systems (Polar-orbiting Operational Environmental Satellites [POES] and Defense Meteorological Satellite Program [DMSP]) under a single national program. Other satellites will include NPOESS Preparatory Project (NPP), Earth Observing System (EOS), and Meteorological Operational Satellite (Metop).

The white paper outlines an operationally driven conceptual framework that will provide an environment to support Climate Data Record (CDR) processing, archiving, and distribution. In contrast to the Environmental Data Records (EDRs) that are planned for NPOESS, CDRs enable errors in the data to be analyzed and quantified in both space and

> **Climate Data Record:** An observational time series of a climate variable that tries to account for systematic errors and noise in the measurements.

time. The production of CDRs requires repeated analysis and refinement of long-term data sets, usually from multiple data sources.

NESDIS will develop a plan to capture the requirements from the CCSP and incorporate results from an NRC workshop on climate data records to be held in August of 2003. It will address key NRC recommendations related to the development of a long-term monitoring system to evaluate decadal and centennial scale changes. In addition, this plan will support the NOAA Strategic Goals adopted March 2003 and the vision of NOAA's Scientific Data Stewardship initiative.

1.2.1 CCSP

In February 2002, President Bush announced the formation of a new management structure, the CCSP, to coordinate and direct the US research efforts in the areas of climate and global change. The CCSP combines under one program the research efforts of the USGCRP authorized by the Global Change Research Act of 1990, and the CCRI launched by the President in June 2001 to reduce significant uncertainties in climate science, improve global climate observing systems, and develop resources to support policymaking and resource management.

The President's CCRI was created to provide a new distinct focus from the 13-year old USGCRP. The CCRI focus is defined by a group of uncertainties about the global climate system that have been identified by policymakers and analyzed by the NRC in a 2001 report requested by the Administration.

One of the three key recommendations from the NRC report "Climate Change Science: An Analysis of Some Key Questions" was to "ensure the existence of a long-term monitoring system that provides a more definitive observational foundation to evaluate decadal- to century-scale changes, including observations of key state variables and more comprehensive regional measurements". The CCRI responded to this NRC recommendation in the CCSP strategic plan with the following statement: "Optimize observations, monitoring, and data management systems of 'climate quality data'. ('Climate quality data' are required for historical perspective, trend analysis, process evaluation, and model development and calibration. These data have particular characteristics including high quality, homogeneity, and continuity; and the availability of full documentation with respect to their technical characteristics)."[7]

The CCSP aims to balance the near-term (2- to 4-year) focus of the CCRI with the breadth of the USGCRP, pursuing accelerated development of answers to the scientific aspects of key climate policy issues while continuing to seek advances in the knowledge of the physical, biological and chemical processes that influence the Earth system.

The strategic plan has been prepared by the thirteen federal agencies participating in the CCSP, with input from a large number of scientific steering groups and coordination by the CCSP staff to provide a vehicle to facilitate comments and suggestions by the scientific and stakeholder communities interested in climate and global change issues.

Development of the NOAA plan for creating climate data records will support the CCSP's, CCRI's, and USGCRP's priorities.

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[7] *Strategic Plan for the Climate Change Science Program*, Final Report, July, 2003.

1.2.2 NOAA Strategic Goals

NOAA's vision is "to move NOAA into the 21st century scientifically and operationally, in the same interrelated manner as the environment that we observe and forecast, while recognizing the link between our global economy and our planet's environment."

Specifically, NOAA will apply its vision to the NOAA mission which is to understand and predict changes in the earth's environment and conserve and manage coastal and marine resources to meet our nation's economic, social, and environmental needs.

To fulfill its mission, NOAA has defined four interrelated goals within its Strategic Plan:[8]

- Protect, restore, and manage the use of coastal and ocean resources through ecosystem-based management
- Understand climate variability and change to enhance society's ability to plan and respond
- Serve society's needs for weather and water information
- Support the nation's commerce with information for safe, efficient, and environmentally sound transportation

It is noteworthy that climate science has been elevated to a high priority goal within NOAA. The NOAA plan for creating climate data records will directly aid NOAA in fulfilling the mission goal: Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond. This goal's measurable outcomes and strategies are shown in Table 1-1.

1.2.3 NOAA Scientific Data Stewardship

The NOAA Scientific Data Stewardship (SDS) is the new paradigm in data management consisting of an integrated suite of functions to preserve and exploit the full scientific value of NOAA's environmental data. These functions include the following:

- Monitoring observing system performance for long-term applications
- Generating authoritative long-term records from multiple observing platforms
- Assessing the state of atmospheric, oceanic, land, cryospheric, and space environments
- Proper archiving and timely access to data and metadata

Successful implementation of scientific data stewardship will ensure that NOAA's environmental data are of maximum use to the Nation now and in the future. The NOAA plan for creating climate data records from operational satellite will address all aspects of the SDS, including issues related to development of climate data records as free of time-dependent biases as possible.

[8] *New Priorities for the 21st Century, NOAA's Strategic Plan for FY 2003-2008 and Beyond*. March 2003.

Table 1-1. NOAA Strategic Goal to Understand Climate Variability and Change

<table>
<tr><th colspan="3">Goal: Understanding Climate Variability and Change to Enhance Society’s Ability to Plan and Respond</th></tr>
<tr><th>Measurable Outcomes</th><th colspan="2">Strategies</th></tr>
<tr>
<td>• Increased use and effectiveness of climate observations to improve long-range climate, weather, and water predictions.

• Increased use and effectiveness of climate information for decision makers and managers.

• Increased use of the knowledge of how climate variability and change affect commerce.</td>
<td>• Monitor and Observe: Invest in high-quality, long-term climate observations and encourage other national and international investments to provide a comprehensive observing system in support of climate assessments and forecasts.

• Understand and Describe: Increase understanding of the dynamics and impacts of coupled atmosphere/ocean/land systems by working with national and international partners to conduct research on climate variability and change.</td>
<td>• Assess and Predict: Provide decision makers with reliable, objective information, by improving the skill and accuracy of intraseasonal and interannual climate forecasts and regional, national, and international assessments and projections.

• Engage, Advise, & Inform: Help customers effectively use climate information to enhance public health and safety; support environmental, economic, and community planning; maximize potential benefits; and minimize the impacts of climate variability.</td>
</tr>
</table>

2 Where Are We Now?

As a first step, NESDIS is in the process of identifying the tools and resources already available and potentially useful in reaching NOAA's goals with regard to climate data records. NOAA and its partners are reviewing the satellite systems in place to identify which data and data systems can supply the measurements and products needed for global climate change research. Identifying what systems are in place will aid in determining what additional capabilities and resources are needed.

Some useful lessons have been learned from reviewing a number of applications of satellite data to specific climate research projects. In some instances, these lessons confirm what was already known about the possibilities and limitations of using existing data sets and systems from space-based observations for climate research. In other cases, the lessons provide new insights on future requirements for data and data management systems in the climate-change research community, distinguishing them from the requirements of operational programs using the same or similar data.

Some progress has been made in reaching a baseline understanding of what is needed via a series of studies, workshops, and other efforts that sought to identify the key science questions for climate research, the data needed to answer the questions, and the key elements of the data management system needed to produce, archive, and provide access to the data.

A number of different climate data records are currently being produced using NESDIS satellite data that are collected routinely for NOAA operational programs such as the National Weather Service (NWS). Either NESDIS generates the climate data internally, or the raw data are provided by NESDIS to external parties who process it in order to produce climate quality products. For some climate quality products, NESDIS is working collaboratively with other parties, for example NASA and researchers in academia.

In addition, NESDIS and its partner agencies have initiated programs that are specifically targeted—either in whole or in part—to support global climate change research. For example, NPOESS, a joint NOAA, DOD, and NASA activity, was initially conceived as a program to provide operational data on Earth's weather, atmosphere, oceans, land, and near-space environment. Subsequently, it was realized that the NPOESS program has tremendous potential to provide data to examine long-term global changes as well. NPOESS instruments now have stability requirements for allowing observations to be used for climate applications. However the NPOESS processing system will produce EDRs, not CDRs. The production of CDRs is not part of the tri-agency NPOESS program. Therefore, NOAA has the responsibility to implement a program for climate applications using NPOESS data.

2.1 Climate Data Records

The climate community has adopted the term Climate Data Record (CDR) to encompass what is more generally described as *climate products*—products that allow study of long-term climate change, for example decadal scale changes in climate variables. The term CDR serves to distinguish these climate products from current operational data sets, Environmental Data Records (EDRs) used to predict weather. Characteristics of EDRs include a tight time constraint due to the need to support real-time analysis, diagnostics, and forecasting; use of past data only to provide an information constraint on the current observations; and an emphasis on minimizing random errors and performing ongoing adjustments (bias correction) for systematic errors. In contrast, CDRs are not as constrained in their production schedule, allowing time for assessment and correction of problems in the data, they use past and future data when analyzing today's data, and they emphasize understanding and minimizing systematic errors as random errors become very small.

2.2 Application of Existing Climate Data Resources and Products to Climate Change Studies

The NOAA/NESDIS operational satellite data program currently collects, receives, distributes, and archives both space-based and ground-based data about climate, including the products shown in the box. Most of the data and products are used in operational programs that rely on real-time data transfer to users, such as weather forecasting. However, many of these data are also processed to produce long-time series records of sufficient quality for climate-change studies. And in some cases, the raw data and metadata are provided to external investigators who produce the climate data records.

The following sections describe some examples of climate products that were derived from existing NESDIS satellite data.

Current NOAA Satellite Products

- **Atmosphere**
  - Temperature soundings
  - Moisture soundings
  - Winds
  - Clouds
  - Aerosols
  - Earth Radiation Budget
  - Precipitation
  - Ozone
- **Ocean**
  - Surface temperature
  - Ice cover
  - Surface winds
  - Color
  - Sea level
- **Land**
  - Vegetation condition
  - Snow Cover
  - Surface Temperature

2.2.1 NOAA Production of Real-Time CDRs from EDRs

NOAA currently produces climate data records using data that were originally collected for operational purposes to produce EDRs. The instantaneous point measurements from EDRs are averaged up to climate scale[9] in a grid and mapped to the Earth's surface to show mean weekly or monthly values. Individual investigators have used a variety of *ad hoc* techniques to adjust the EDRs for systematic errors due to changes in the satellite instruments or other biases in the data sets.

Since the beginning of the current NOAA operational series of polar-orbiting satellites in late 1978, a variety of products useful for climate monitoring have been produced. Table 2-1 summarizes these products; examples of uses of these data are given below.

Earth Radiation Budget (ERB) Products

Earth Radiation Budget (ERB) data are fundamental to understanding the global energy balance. ERB is the difference between the radiation incident on the Earth from the sun and the radiation leaving the Earth into space. NOAA Radiation Budget products include daily and monthly mean

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[9] The term *climate scale* generally refers to spatial averages on the order of 100 km and temporal averages on the order of weeks or months.

global maps of outgoing long-wave (infrared) radiation and absorbed and available incoming shortwave (solar) radiation. Figure 2-1 shows a recent monthly mean product for absorbed solar energy.

Table 2-1. NOAA Near–Real-Time CDRs Produced from EDRs

Climate Product	Satellite/ Instrument	Spatial/temporal resolutions	Since	Physical Basis	Where archived
Earth Radiation Budget (ERB) Outgoing long-wave radiation (OLR) Absorbed solar radiation (ASR)	POES/AVHRR	250 km/month	1978	OLR and ASR correlated with AVHRR IR and VIS window observations	NCDC
Sea Surface Temperature (SST)	POES/AVHRR	50, 100, 250 km/month	1981	Split window	NCDC
Vegetation Normalized Difference Vegetation Index (NDVI) Drought Index	POES/AVHRR	16 km/week	1985	Reflectance difference between NIR and VIS depends on vegetation amount and health Current GVI relative to historical max and min GVI	NCDC Experimental Product
Drought Index	POES/AVHRR	16 km/week	1985	Current GVI relative to historical max and min GVI	Experimental product
Aerosols Aerosol Optical Thickness (AOT)	POES/AVHRR	1 degree	1988	Sunlight reflected by aerosols	NCDC

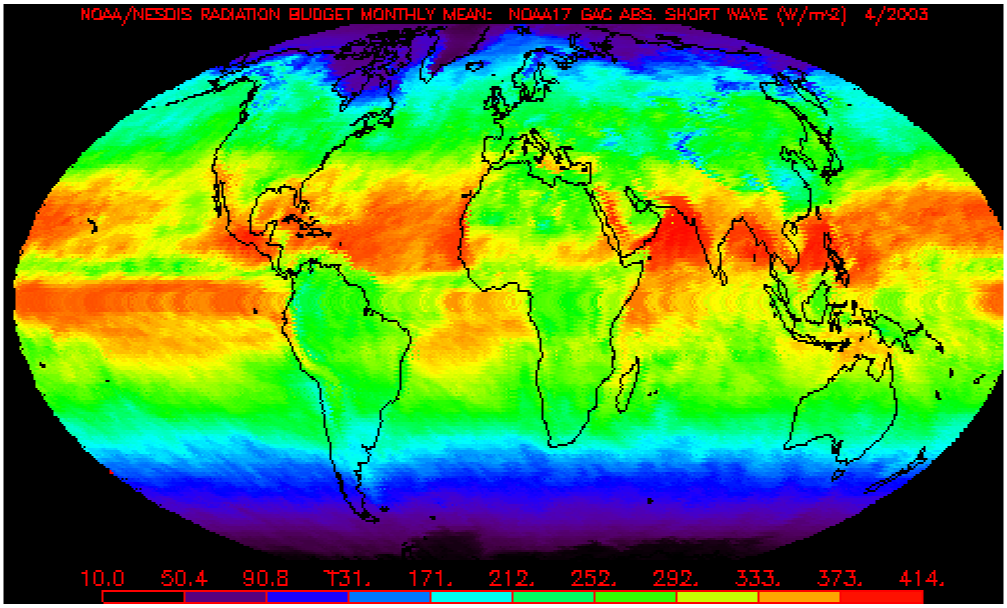


Figure 2-1. May 2003, Monthly Mean Absorbed Solar Energy NOAA-17 AVHRR

Source: http://www.osdpd.noaa.gov/PSB/EPS/RB/RB.html

The outgoing long-wave radiation (OLR) product is used by a variety of researchers to monitor the variability of deep convection in the tropics and as a rainfall index. Figure 2-2 shows how NOAA's Climate Diagnostics Center uses this data set to provide real-time monitoring of equatorially-trapped atmospheric wave modes by identifying time-space variations of OLR. Modes of atmospheric variability identified include the Madden-Julian Oscillation (MJO), equatorially-trapped Rossby waves (ER1), and atmospheric Kelvin waves.

Sea Surface Temperature (SST)

Sea surface temperature (SST) is the skin temperature of the ocean surface water. NOAA/NESDIS products include composite gridded images on a global scale, an example of which is shown in Figure 2-3. An example of the validation of SSTs against ocean buoy observations is provided in Figure 2-4.

Blended SST products are produced by NOAA's Climate Prediction Center within the National Weather Service (NWS) using satellite, buoy and ship data. The data for buoy SST are used to minimize artificial cooling from atmospheric aerosols and to correct for biases in the satellite sensor. Temporal and spatial averaging provides complete global oceanic coverage and eliminates cloud contamination.

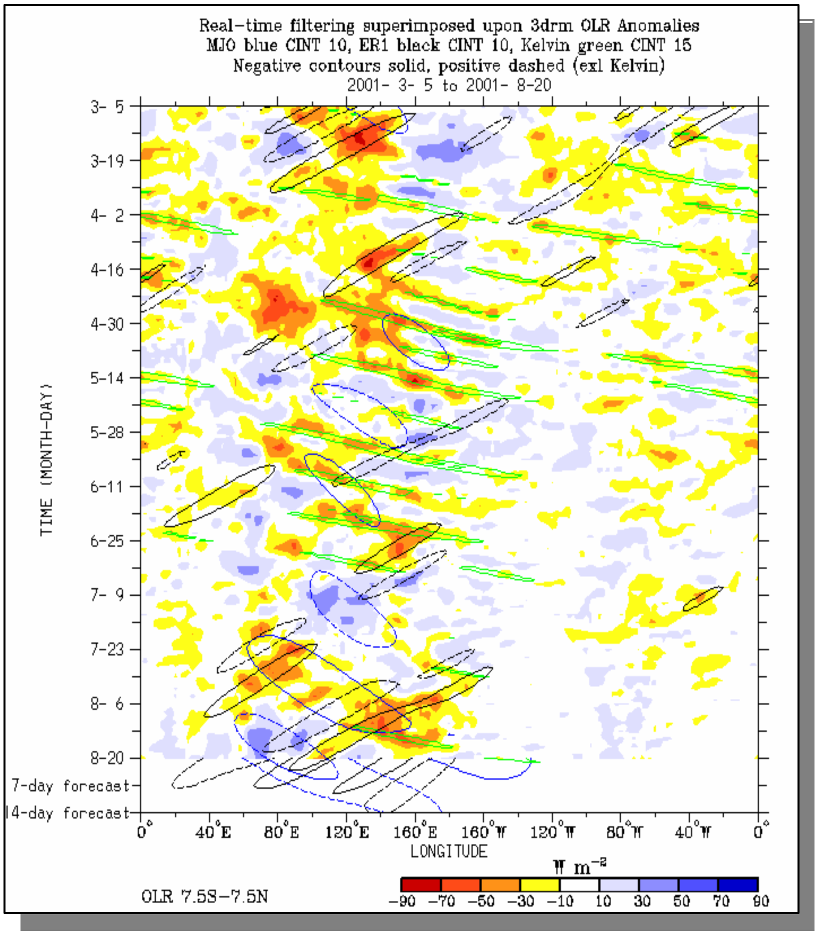


Figure 2-2. Real-Time Filtering Superimposed on Three-Day Running Mean OLR Anomalies

Source: http://www.cdc.noaa.gov/map/clim/olr_modes/

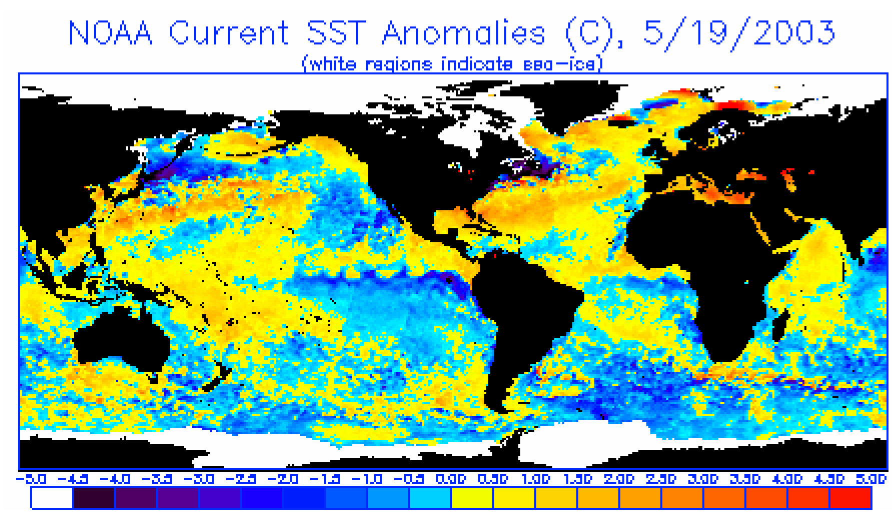


Figure 2-3. SST Anomalies May 19, 2003

Source: http://www.osdpd.noaa.gov/PSB/EPS/SST/climo.html

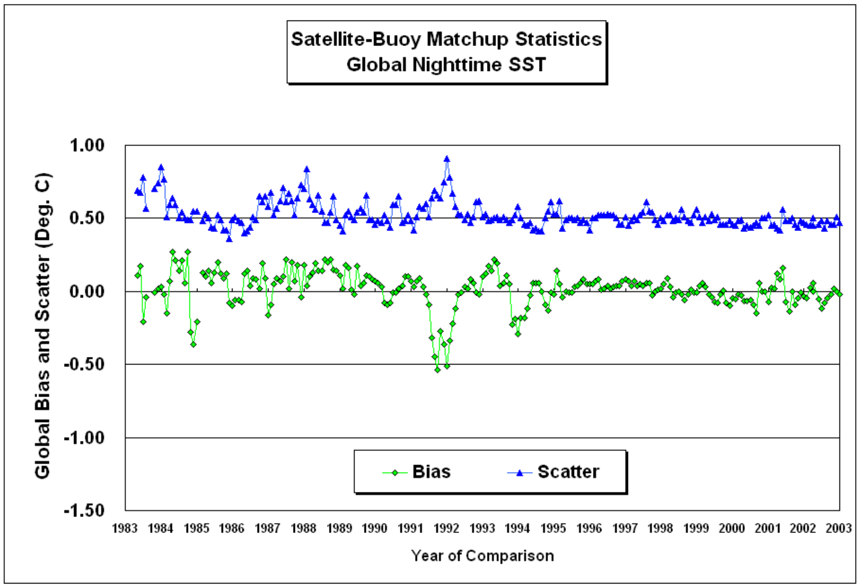


Figure 2-4. Validation of Satellite SSTs

Source: NESDIS/ORA

Researchers at NOAA's NCDC have also produced a monthly extended reconstruction of global SST (ERSST) based on observations from 1854-1997.

Vegetation Index (GVI)

The Vegetation Index is a measure of the amount and health of vegetation on the Earth's surface. Combined with data on surface temperature, it provides useful information on drought conditions. Vegetation sources and sinks for carbon dioxide vary with land cover and land use. Measurements of vegetation cover and conditions also provide critical information needed to determine carbon budgets, changes in land use (which often change the vegetation cover significantly), and to quantify greenhouse gases.

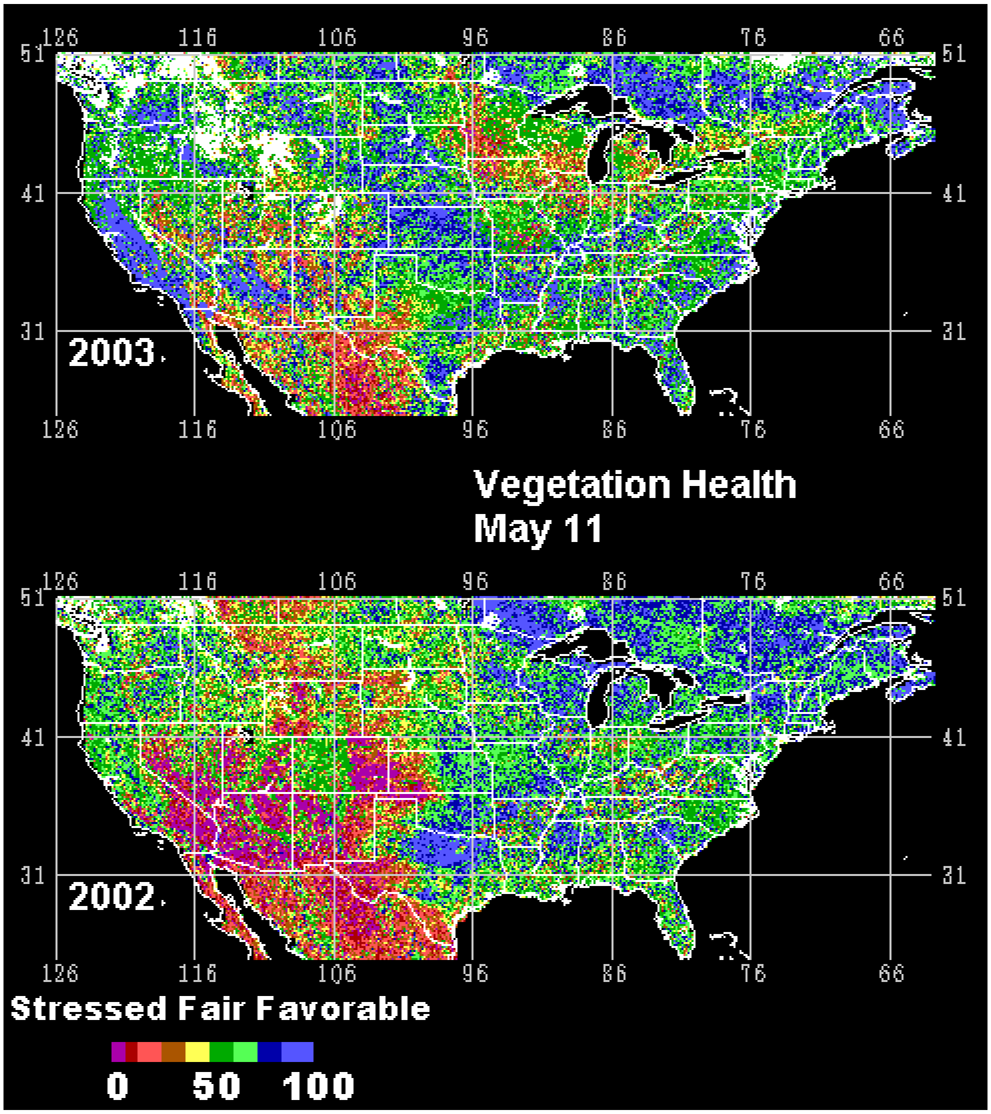
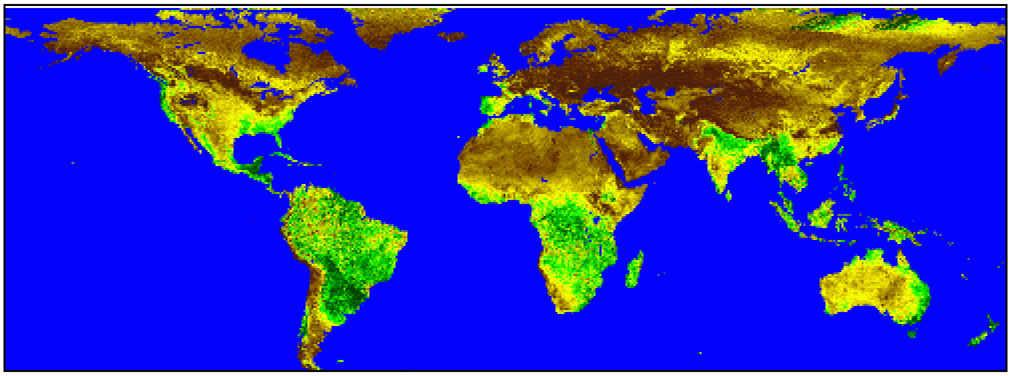


Figure 2-5. Vegetation Index May 11, 2003

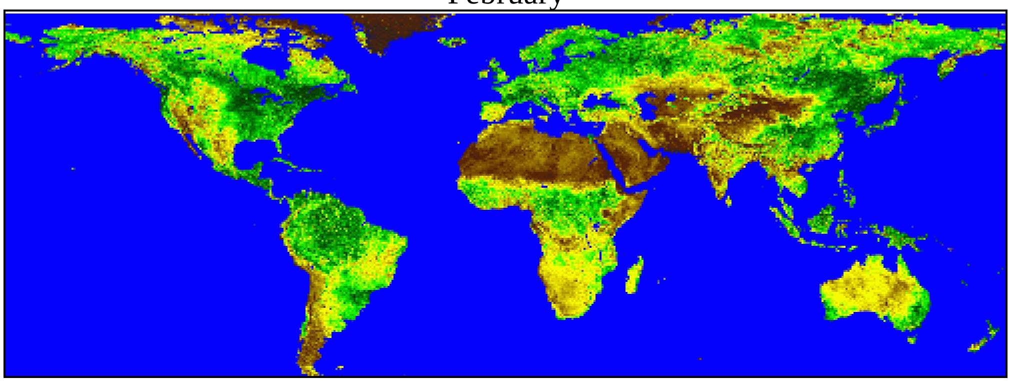
Source: http://orbit-net.nesdis.noaa.gov/crad/sat/surf/vci/usa.html

Aerosols

Whether from anthropogenic or natural sources, aerosols in the atmosphere reflect sunlight back into space, potentially compensating for some of the warming effects of increased carbon dioxide releases to the atmosphere. There is enormous uncertainty about the magnitude of this effect on the earth's radiation budget. And in fact, some aerosols actually have a warming effect. NOAA currently monitors atmospheric radiation budget, cloud cover, and aerosol content using AVHRR. Products for Aerosol Optical Thickness (AOT) are available through NCDC for data collected since November 1988. The primary products are global ocean maps of AOT based on a composite of one week's worth of data, and the monthly mean product.



February



August

Figure 2-6. NOAA/GVI Eight-Year (1983-90) Mean Maximum

Source: Produced for the World Atlas of Desertification by UNEP in 1992,
http://www.grid.unep.ch/data/grid/images/gnv179.php

DMSP SSM/I Products

NESDIS develops and validates SSM/I (Special Sensor Microwave/Imager) algorithms for application in weather forecasting and analysis as well as climate evaluation. The SSM/I, an instrument operated under the Defense Meteorological Satellite Program (DMSP) became operational in July 1987.[10] SSM/I products are useful for evaluating the mean climate state, interannual, and seasonal variations, and the detection of anomalies associated with ENSO and regional climatic variations. Monthly average products are available for precipitation, cloud liquid water, total precipitable water, snow cover, sea-ice cover, and oceanic surface wind speed. The data are archived and accessed through the NOAA/NESDIS National Climatic Data Center (NCDC). Details for some of the products are given in Table 2-2.

[10] The SSM/I will be replaced by a more advanced sensor, the SSMIS (Special Sensor for precipitation, cloud liquid water, total precipitable water, Microwave Imager Sounder) in 2003.

Table 2-2. NOAA DMSP SSM/I Climate Products

	Physical Basis of Measurement	Spatial Resolution (grids from 30 km sensor resolution)	Produced since
DMSP SSM/I Product			
Rainfall	Scattering by hydrometeors	100 km grids 250 km grids	July 1987
Snow Cover	Snow grain scattering		
Sea Ice Cover	Ice absorption		
Clouds : Liquid water path (under cloudy conditions) (LWP) Mean cloudiness Fraction (CFR)	Droplet absorption		
Total water vapor	Water vapor emission		
Oceanic Surface Wind Speed	Ocean emissivity depends on ocean surface roughness		

2.2.2 NOAA/NASA Collaborations

Production of Ozone CDRs

SBUV/ozone products are produced via a NOAA/NASA partnership. NASA develops the processing algorithm and characterizes the instrument; NOAA performs real-time and retrospective processing, validates the CDRs against ground-truth data, and develops seamless time series from the multi-satellite data set. These products are currently generated from the systems flying on NOAA-11, NOAA-14, and NOAA-16 satellite instruments (SBUV/2/POES, Solar Backscattered Ultraviolet Radiometer/Version 2).

Table 2-3. Ozone Products

Climate Product	Satellite/Instrument	Spatial/temporal resolutions	Since	Physical Basis	Where archived
Ozone (total and stratospheric profile)	POES/SBUV/2	200 km/daily	1985	Backscattered ultraviolet radiance	NCDC
Ozone (total)	POES/ATOVS/HIRS	40 km	1979	Ozone infrared emission	NCDC

ERBE

For NASA's Earth Radiation Budget Experiment (ERBE) that began in 1984, NOAA provided space on four POES satellites for NASA to fly its Active Cavity Radiometer Irradiance Monitors (ACRIM), instruments developed by NASA to provide radiation measurements. These instruments have provided data on the temporal and spatial variation of the earth's radiation budget (ERB) from 1985-1999. Recent work by Wielicki et al. using the ERBE/ERBS nonscanner OLR data has suggested a significant decadal jump on OLR occurred in the early 1990s (Figure 2-8). This trend is not supported either by analysis of the NOAA/HIRS Path A Pathfinder data or by the operational NOAA/AVHRR OLR data.

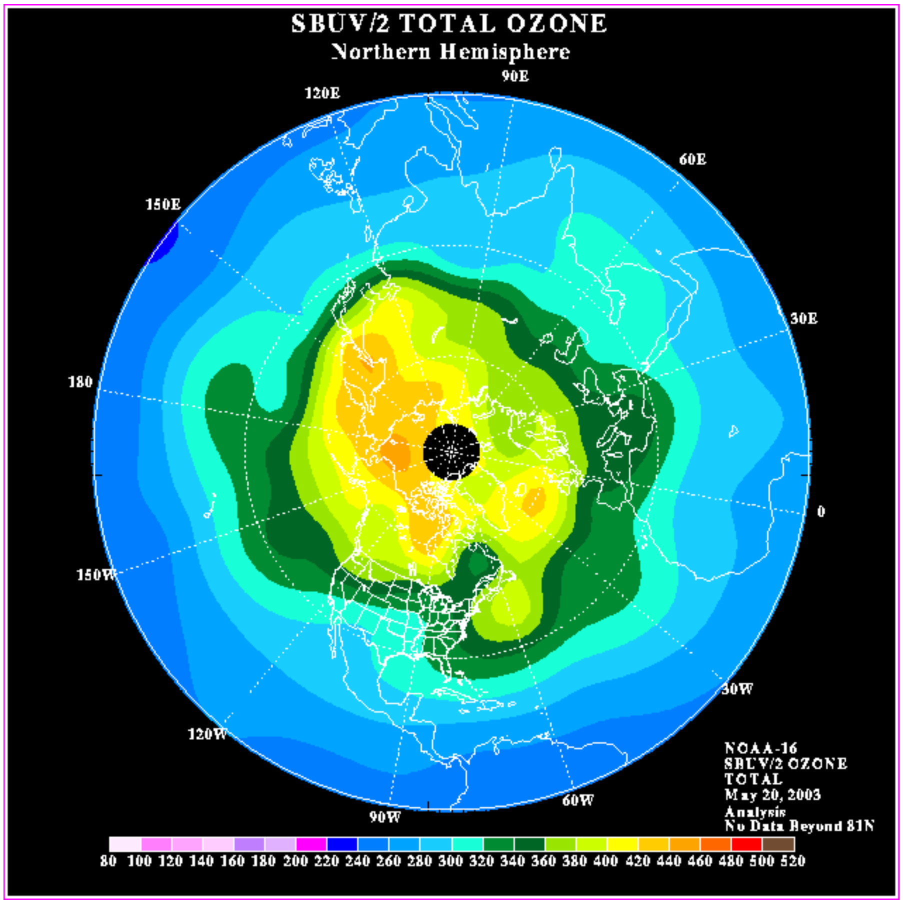


Figure 2-7. Total Ozone, Northern hemisphere, SBUV/2, May 20, 2003

Source: http://www.cpc.ncep.noaa.gov/products/stratosphere/sbuv2to/sbuv2to_latest.html

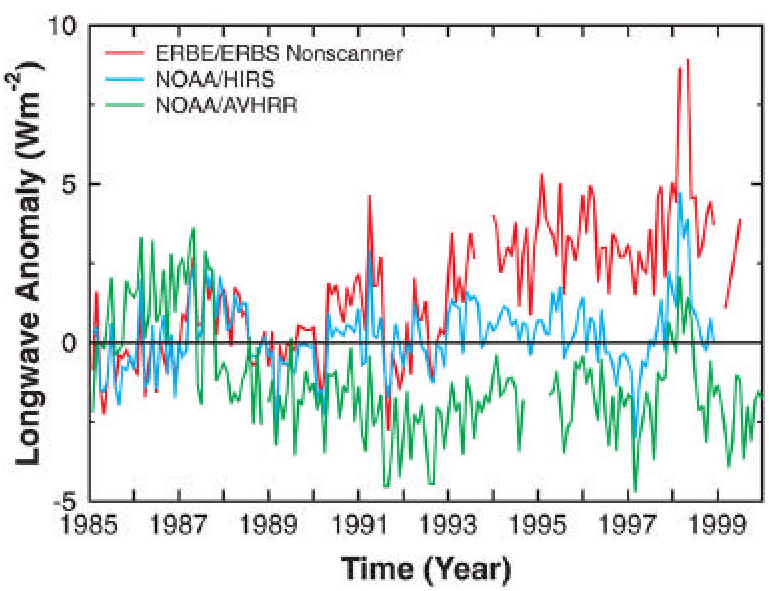


Figure 2-8. Significant Decadal Jump in OLR in Early 1990s

Source: http://www.sciencemag.org/cgi/content/full/295/5556/841/DC1

2.2.3 Production of CDRs by External Teams

NESIDS also provides instrument level data and EDRs to external researchers who process the data to meet CDR requirements. Two examples follow.

MSU Temperature Products

Microwave Sounding Units (MSU) observations from POES satellites are being used to study long-term trends in temperature in the lower atmosphere (troposphere). The four frequency channels measure emitted microwave radiation (sensitive to atmospheric temperature) of four layers of the atmosphere. Channel 2 measures the temperature of the middle to upper troposphere, where a small fraction of the radiation actually originates in the lower stratosphere. This contribution from the stratosphere must be accounted for in climate change studies, because in a greenhouse warming scenario tropospheric warming will be accompanied by stratospheric cooling. In addition, the orbital drift of the satellites causes variation in temperatures due to the change in time of day the measurements are taken. Climatologists at the University of Alabama (John Christy and Roy Spencer) have analyzed the MSU data to correct for the stratospheric contributions to temperature as well as for a number of artifacts in the data (e.g., orbital drift of the satellites). Figure 2-9 shows an example of a reconstructed time series produced with this approach.

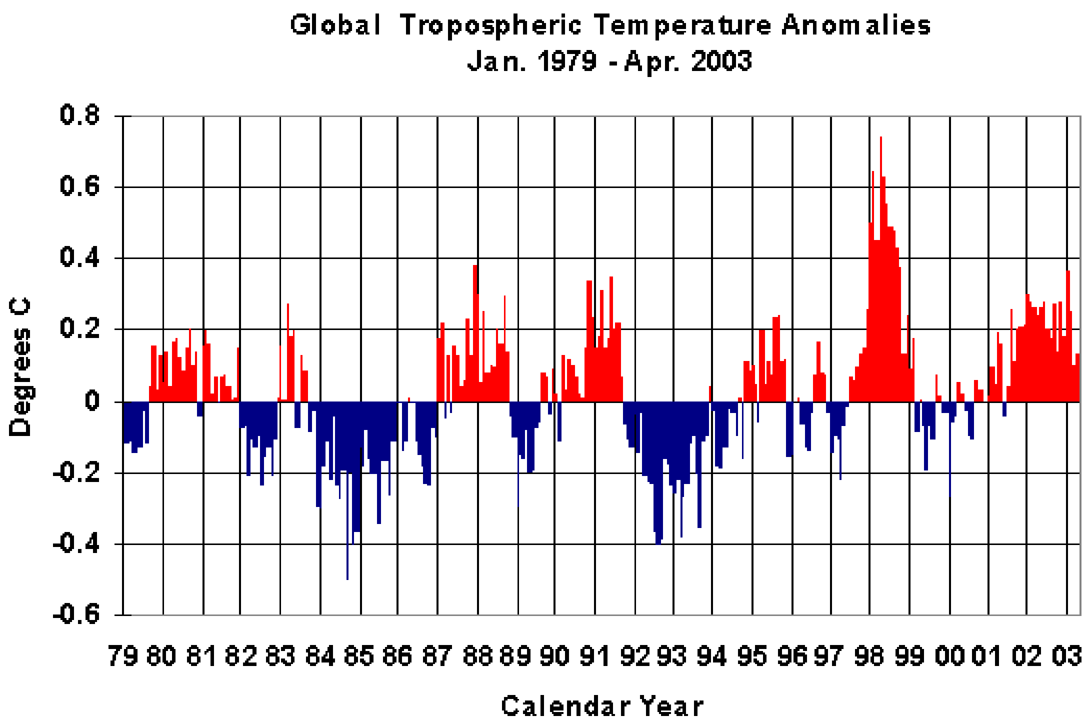


Figure 2-9. MSU Data Corrected for Orbital Drift

Source: http://www.ghcc.msfc.nasa.gov/ghcc_cvcc.html

Table 2-4. CDRs Produced by External Investigators

Climate Product	Satellite/Instrument	Spatial/temporal resolutions	Since	Physical Basis	Where archived
Atmospheric Temperature[11]	POES/MSU	Regional to Global/Monthly	1979	Microwave emission by oxygen	GHCC[12]
Snow Cover[13]	POES/AVHRR, GOES, Meteosat, GMS Visible imagery, DMSP SSM/I	180 km/weekly	1966	Reflected sunlight and emitted microwave radiation	Snow Data Resource Center

Snow Products

NESDIS produced snow products from 1966-1971; however these products were not considered accurate. Researchers at the Rutgers University Climate Laboratory's (RUCL) Snow Data Resource Center reanalyzed the products from 1966 to 1971 and improved their accuracy. After 1971, NESDIS upgraded its product and is now producing snow products accurate enough for climate purposes. Currently, Rutgers further refines NESDIS products and aggregates the information into snow cover areas to 180 km, and produces snow coverage maps for the Northern Hemisphere over the last 37 years, including monthly hemispheric snow cover and 33 year climatology maps updated monthly. An example is shown in Figure 2-10.

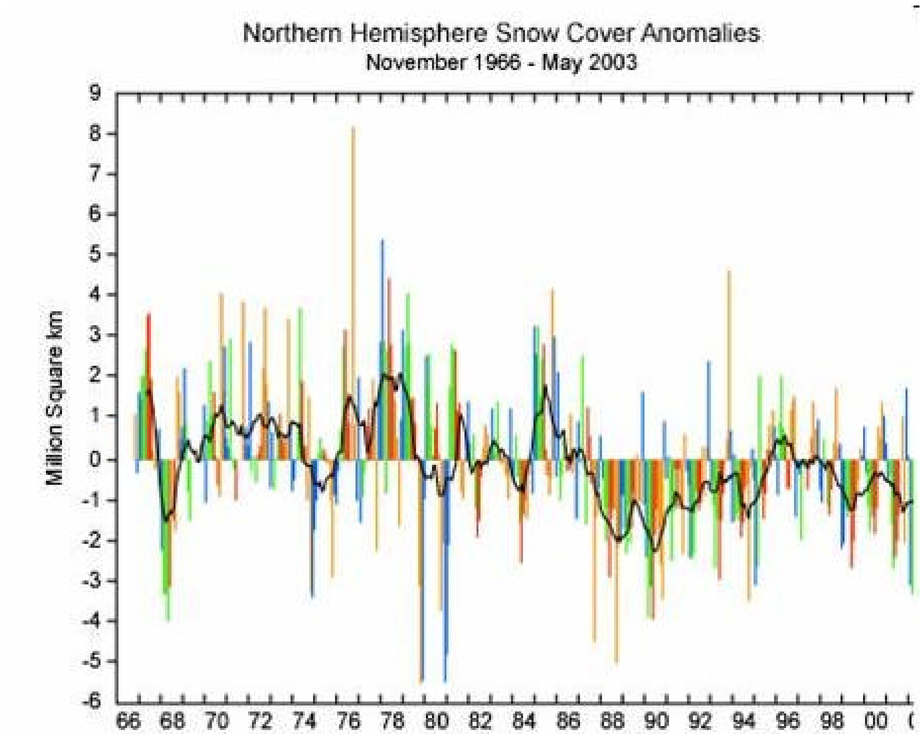


Figure 2-10. Northern Hemisphere Snow Cover Anomalies

Source: http://climate.rutgers.edu/snowcover/anomalies.php?ui_region=nhland&x=110&y=21

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[11] Christy, et al. data http://www.ghcc.msfc.nasa.gov/MSU/msusci.html
[12] Global Hydrology and Climate Center
[13] Rutgers work http://climate.rutgers.edu/snowcover/datahist.html; image is snow cover for March 2003

2.2.4 One-Time Processing Programs: Pathfinder Program

NOAA and NASA initiated the "early-EOS Pathfinder Data Set Activity" in 1990 to produce long time series data sets for global climate change research by re-processing existing satellite data sets using community consensus algorithms. Most of the data are from NOAA satellite instruments designed for weather applications.

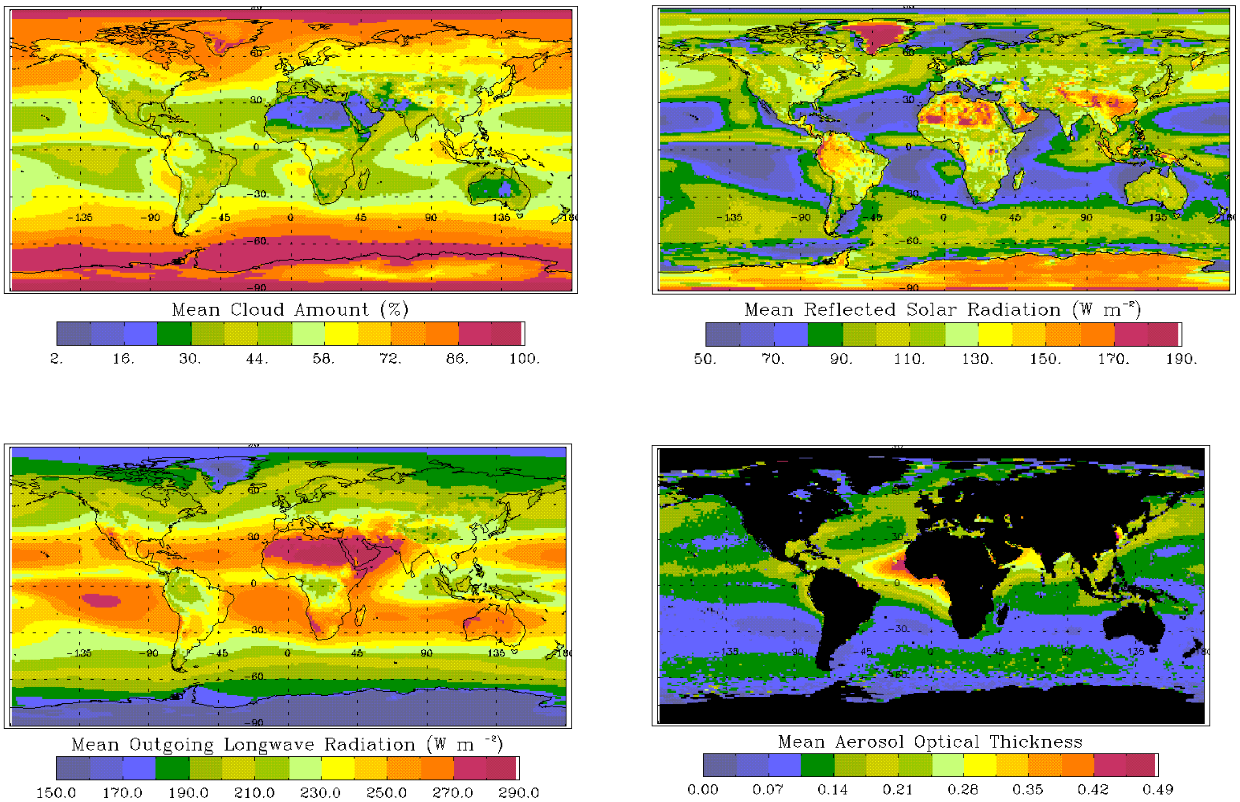

Figure 2-11. Annual Mean Global Maps of Reflected Solar Radiation, Cloud Amount, Outgoing Long-Wave Radiation, and Aerosol Optical Thickness, based on 20 years of AVHRR observations

Source: Bulletin of American Meteorology Society, June, 2003

Under the AVHRR Pathfinder Atmosphere (PATMOS) project, NOAA has reprocessed 20 years of AVHRR Level 1 data[14], correcting the radiances for calibration drift, to provide daily, five-day, and monthly averaged products for cloudy and clear radiance statistics, total cloud count, top of the atmosphere radiation budget (cloudy and clear sky) and aerosol optical thickness over oceans.

[14] Level I data are raw sensor data which have been pre-processed. Level 1a denotes data that have been extracted but not formatted into time-sequenced data sets; Level 1a formats are internal NOAA formats that are used only for NOAA processing to create the Level 1b data. Level 1b denotes discrete, instrument-specific data sets that are time-referenced, and to which Earth location and calibration information have been appended (but not applied).

The TOVS Radiance Pathfinder project provides a 23-year climatology of clear-sky radiances, cloud retrievals and upper tropospheric humidity using the TOVS/ATOVS instruments aboard the NOAA polar-orbiting satellite series.

Figure 2-12 depicts the following:

- Upper tropospheric humidity climatology shows distribution of tropical monsoon-desert system.
- 20-year trend shows increasing UTH along equator and east Asia, decreasing UTH in subtropics.
- Confidence levels show only largest trends are significant – confidence intervals are computed using linear scatter, lag-1 autocorrelation, and length of record vs. trend.

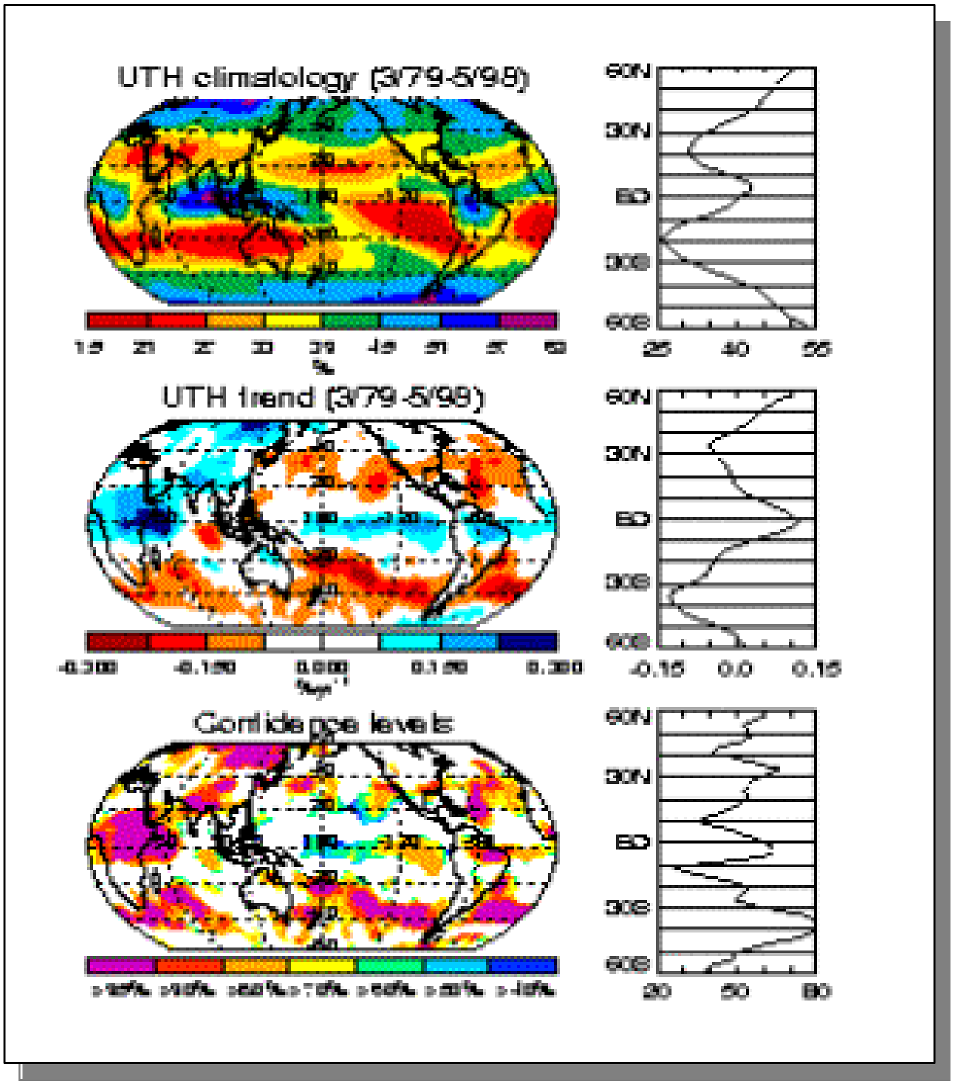

Figure 2-12. Examples of Upper Tropospheric Humidity (UTH) Products

Source: http://www.etl.noaa.gov/satres/archive.html

NOAA/NASA Pathfinder Programs

- AVHRR Pathfinders
  - Atmospheres
  - Land
  - 1-km Land
  - Oceans
- TOVS
  - Path A
  - Path B
  - Path C1
  - Path C2
  - Polar Path
- GOES
  - Level 2 products
  - Level 3 earth-gridded data
- Landsat
  - North American Landscape Characterization (NALC) Satellite Imagery
  - Humid Tropical Forest Inventory Project
- Ocean Altimetry
- Polar Regions

Source: NCDC/NOAA/NASA Pathfinder Climate Data Collection

2.2.5 Production of CDRs by International Projects

Climate products that are used to study the role of clouds in climate and the effects of clouds on the earth's radiation balance are produced through the International Satellite Cloud Climatology Project (ISCCP) as part of the World Climate Research Programme (WCRP). Sector Processing Centers (SPCs) in the United States (funded by NOAA), Canada, Japan and Germany collect raw satellite data for their respective satellite image areas and prepare and deliver condensed radiance data sets to the Global Processing Center (GPC) at NASA's Goddard Institute for Space Science where the three hour and monthly mean global cloud properties data are derived and sent to the ISCCP Central Archive at NOAA. ISCCP is an example of multi-satellite generation of a CDR.

The Global Precipitation Climatology Project (GPCP) began in 1986 with an initial goal to provide monthly mean precipitation data for 1986-1995[15] by merging infrared and microwave satellite estimates with rain gauge data from over 30,000 stations. The infrared data are obtained from POES and Geostationary Operational Environmental Satellite (GOES), GMS (Japan), and Meteosat (European) geostationary satellites. The microwave data are obtained from DMSP SSM/I sensors. These products are being used in climate change studies and to validate general circulation and climate models.

[15] recently extended to 2000.

Table 2-5. Production of CDRs by International Projects

Climate Product	Satellite/Instrument	Spatial/temporal resolutions	Since	Physical Basis	Where archived
ISCCP Cloud Products	POES/AVHRR GOES/METEOSAT/GMS	30 km/monthly mean	1983	Reflected sunlight and emitted IR radiation	NCDC
GPCP	POES/AVHRR GOES DMSP/SSM/I Meteosat GMS Visible IR imagery	[2.2 degree grid]	1986	Microwave emission by oxygen (MSU); emitted IR radiation (GOES)	NCDC

2.3 NPOESS/NPP Program

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) will be a satellite system used to monitor global environmental conditions, and collect and disseminate data related to weather, atmosphere, oceans, land and near-space environment. The NPOESS program was initiated in response to the recognition in 1994 that converging the existing polar systems from the Department of Commerce (DOC) and Department of Defense (DOD) would result in a more cost effective and higher performance integrated system. In addition, NPOESS will provide a transition from NASA's Earth Observing System (EOS) Terra and Aqua missions to continue the quantitative environmental satellite measurements that are needed to produce climate-quality observations.

The NPOESS program is managed by the tri-agency Integrated Program Office (IPO), employing personnel from the DOC, DOD and the National Aeronautics and Space Administration (NASA). NPOESS was initially conceived as primarily an "operational" program to provide real-time data for weather prediction, disaster preparedness, and national security. Realizing that NPOESS also offers significant opportunities for collecting and processing data of climate quality, NOAA is now incorporating planning efforts targeted to support climate change studies under the NPOESS program. The mature NPOESS program will be the primary source for most satellite-derived climate data.

The NPOESS Preparatory Project (NPP) is a joint NASA/IPO project designed to make the transition to NPOESS efficient and to minimize risk through early testing of instruments, systems, and products. The lessons learned through the NPP will allow modifications to design prior to the NPOESS launch, improvements in support of ground systems, and optimization of NPOESS data products, algorithms, instrument verification, and instrument calibrations. NPP planning includes consideration of the requirements for climate quality data products, such as refined algorithms, conservation of metadata, and development of sensors that will support the data needs of both the operational and climate research communities.

NPP will function as a bridge between the NASA EOS program and NPOESS for development of the following sensors:

- Visible/Infrared Imager Radiometer Suite (VIIRS)
- Cross-track Infrared Sounder (CrIS)

- Advanced Technology Microwave Sounder (ATMS)
- Ozone Mapping and Profiler Suite (OMPS)

Initially, a competitively selected NPP Science Team will assess the potential to produce CDRs from related NPOESS EDRs. A second NPP science team will determine how other NPOESS operational data sets can be enhanced with improved algorithms, added ancillary data, or with other processing steps in order to produce CDR test data sets that can be compared to similar, past sets for verification. The CDRs that are derived will be provided to the NOAA Long-Term Archive (LTA) for distribution to the user community.

Ultimately, the science team and NPP staff will prepare a science operations concept document defining how CDRs will be produced, validated, stored and distributed during the NPP mission. This document and the results of the algorithm analysis will be used to refine the draft NPP Calibration/Validation Plan.[16] Throughout the development of NPP climate products, science team members will draw on the lessons learned from Pathfinder, AIRS/AMSU/HSB, and MODIS activities.

NPP will provide data on atmospheric and sea surface temperatures, humidity soundings, land and ocean biological productivity, cloud and aerosol properties, snow cover and sea ice, and atmospheric ozone.

NOAA is preparing for the enormous increases in environmental data volumes over the next 15 years as NPOESS and other NOAA programs rapidly expand the archive and access requirements for environmental data. Increased data handling capacity will be provided by the Comprehensive Large Array-Data Stewardship System (CLASS). CLASS is designed to allow rapid expansion in storage capacity at NOAA Data Centers and efficient management of the petabytes of data that are critical to the climate scientific community.

[16] Available at http://jointmission.gsfc.nasa.gov/science/calibration.html

3 Lessons Learned in the Use of Satellite Observations for Climate Monitoring

Efforts to use the operational environmental satellite observations over the past decade or more has resulted in a set of recommendations from researchers that have recently been formalized by the climate community into satellite climate observing principles. These include the following:

- Rigorous station-keeping should be maintained to minimize orbital drift.
- Overlapping observations should be ensured for a period sufficient to determine inter-satellite biases.
- Satellites should be replaced within their projected operational lifetime (rather than on failure) to ensure continuity (or in-orbit replacements should be maintained).
- Rigorous pre-launch instrument characterization and calibration should be ensured.
- Adequate on-board calibration and means to monitor instrument characteristics in space should be ensured.
- Development and operational production of priority climate products should be ensured.
- Systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained.
- Continuing use of still-functioning baseline instruments on otherwise de-commissioned satellites should be considered.
- The need for complementary in-situ baseline observations for satellite measurements should be appropriately recognized.
- Network performance monitoring systems to identify both random errors and time-dependent biases in satellite observations should be established.
- Multiple observing and analysis techniques for critical climate data records should be used.

The first five of these principles generally have to do with engineering and maintenance of satellite instruments and are largely the purview of the satellite agency. These are important recommendations, but are beyond the scope of this study. In contrast, the second six principles are essential topics for discussions and recommendations of this report. They spawn a number of important questions that are further discussed in the next section including the following:

- What are the priority climate products that an operational center should produce and how?
- What methods and good practices should be used to facilitate access to a variety of products, metadata, and raw data?
- What in situ baseline observations are required for long-term calibration and validation of space-based observations?
- What critical performance measures should be monitored in real-time to avoid single-point failures in long-term records of critical climate variables?
- How do we reconcile different observations and analysis techniques to achieve the best and/or consensus climate data records?
- What is the role of data assimilation into numerical models in the generation of climate data sets?

3.1 Understanding the Forward and Inverse Radiative Transfer Problems

The process of using satellite data for climate applications is complex (Figure 3-1). The ultimate goal is to better understand the satellite data and then apply this understanding to process studies of climate applications leading ultimately to improved climate predictions and information on historical climate trends and variability. There are, in general, two paths to reaching this goal, the forward problem and the inverse problem. In the forward problem, sample geophysical variables are run through a forward radiative transfer model, along with specific information about the satellite instrument such as the instrument error characteristics and spectral response functions, and the outputs are simulated radiances. This process gives us an idea of what performance we might anticipate from a given instrument. The inverse problem begins with the actual satellite observations. These observations are then used with an inverse radiative transfer model to produce retrievals of geophysical variables. In this process, additional constraints are often applied to the satellite observations such as use of a forecast first guess, other *a priori* data such as clustered radiosonde observations, and radiance bias corrections. Observed radiances are compared to simulated radiances and retrieved geophysical variables are compared to observed geophysical variables and this knowledge is then applied to process studies of climate.

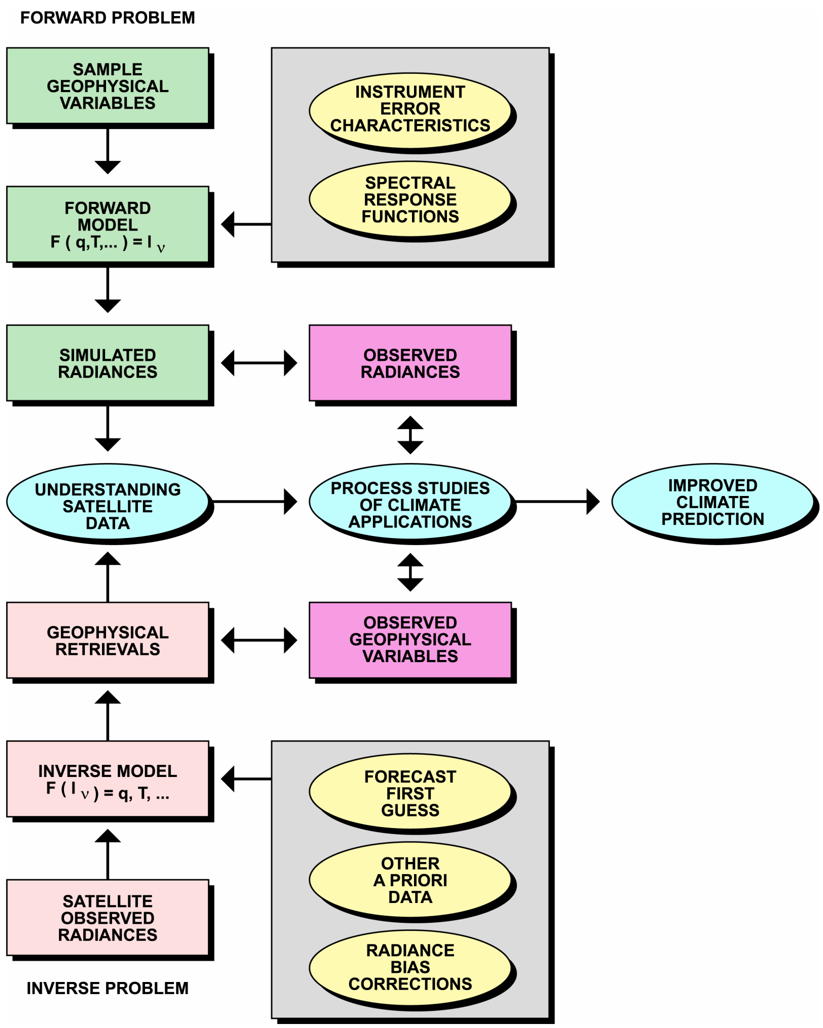

Figure 3-1. Processing Satellite Data for Climate Applications

The linear inversion problem from satellite radiance observations can be expressed as:

$$\hat{x} - x_0 = W \bullet (y_m - y_c\{x_0\})$$

where,

$\hat{x}$ is the vector of retrieved atmospheric parameters

x_0 is the first-guess value of the vector

y_m is the vector of multi-channel radiance measurements

$y_c\{x_0\}$ is the corresponding vector appropriate to the first guess

W is the 'inverse matrix'

The inverse matrix W can be obtained through a minimum variance solution via:

$$W = (K \bullet C)^T \bullet (K \bullet C \bullet K^T + E)^{-1}$$

where,

C is the error covariance of the first guess, x_0

E is the error covariance of the measurements, y_m

K contains the partial derivatives of the measurements with respect to the profile evaluated at x_0

superscripts T and –1 denote matrix transpose and inverse

The linear approximation to the forward radiative transfer problem is:

$$y_m - y_c\{x_0\} = K \bullet (x_T - x_0) + e_m$$

where,

x_T is the vector of true geophysical parameters

e_m is the vector of measurement errors, assumed to be random, Gaussian, unbiased and includes unbiased errors in the forward radiative transfer model

Combining the forward and inverse radiative transfer equations and rewriting it in terms of the retrieval, first-guess and random measurement errors yields:

$$\hat{x} - x_T = (I - R) \bullet (x_0 - x_T) + W \bullet e_m$$

where I is the identity matrix and $R = W \bullet K$

By taking large averages, as is done in climate studies, $e_m \rightarrow 0$, the systematic retrieval errors are determined by the R matrix and the systematic errors in the first guess as demonstrated by Eyre (1987).

Figure 3-2. Error Characteristics of the Forward and Inverse Problems

Figure 3-2 describes the error characteristics of forward and inverse problems. The application of these models has profound implications for the use of satellite observations for producing climate data records. The systematic errors in the first guess can be eliminated by a judicial choice of how to use the first guess information such as choosing a cluster weighted centroid of the first guess information rather than a single profile vector. The more difficult issue is minimizing the complex and non-linear systematic errors associated with the retrieval matrix R. In general, any systematic errors in the raw satellite observations will be amplified by application of the retrieval matrix. Thus, first and foremost, any instrumental and other spacecraft errors (e.g., time drift or change in spacecraft height) must be removed before attempting to perform a retrieval. It is critical that such errors be identified as soon as possible in the data stream and that there be an ongoing program to document and correct these errors.

3.2 Need for a Systematic Assessment of Instrument Quality

All efforts to produce long-term climate records from operational satellite require that there be multiple levels of calibration and intercalibration. The first climate processing system to recognize this explicitly was the International Satellite Cloud Climatology Program (ISCCP). The ISCCP processing scheme uses three levels of calibration: 1) the nominal calibration, 2) the satellite inter-calibration, and 3) the vicarious calibration. Nearly all attempts at producing climate data records use some variation of this basic scheme. The ultimate goal is to provide an absolute calibration standard for space-based instruments against a laboratory standard. We are, however, a long way from doing this which is why a multi-step process such as that applied by ISCCP will be required for some time into the future.

3.2.1 Nominal Calibration

The nominal calibration involves the best practices and understanding of the calibration of a single instrument on a single spacecraft. Depending on the instrument, various parameters are monitored and examined in order to provide the best characterization of a single instrument's performance including pre-launch characterization, post-launch commissioning and characterization, and in-flight performance. Figure 3-2 shows an orbit-by-orbit statistical summary of the in flight performance of HIRS Channel 4 (an upper tropospheric temperature sounding channel using emission from CO2) for one year.

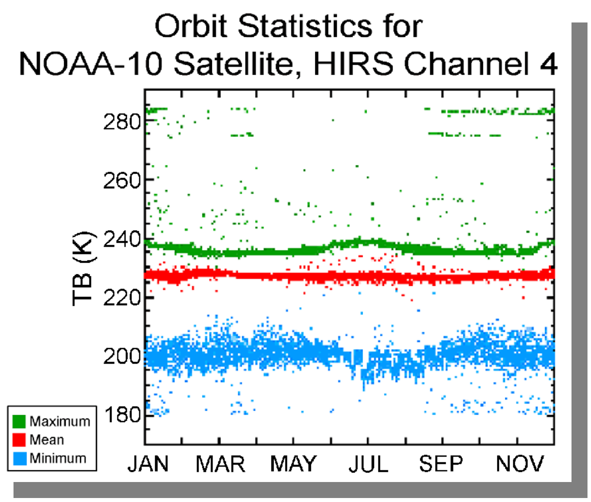

Figure 3-3. Orbit-by-Orbit Summary for One Year

3.2.2 Intercalibration

An example of intercalibration is adjusting a series of same-generation instruments to a particular instrument and spacecraft for a variety of physical processes that result in systematic biases or instrument drift. There are numerous physical processes that can contribute to such biases and every effort should be made to understand the physical cause of the bias in order to apply a physically consistent correction. Some of the processes that have been identified as resulting in instrument biases and drift include: uncertainties in pre-launch instrument response characterization, instrument optics including deposition of contaminants (for example frozen CO_2) on mirror surfaces, drift of the satellite orbit in time and altitude, electronic noise and cross-talk. Each cause of bias must be addressed on a first principles physics basis to the extent possible. In the end, however, we are often required to adopt ad hoc corrections to eliminate residual biases in order to produce long-term, seamless time series. Where possible, multiple techniques for performing the nominal calibration should be used. The following figure shows the impact of intercalibration on a MSU channel 2 time series. Without any adjustments, the trend is 0.35 K; the trend from the intercalibrated time is 0.05 K.

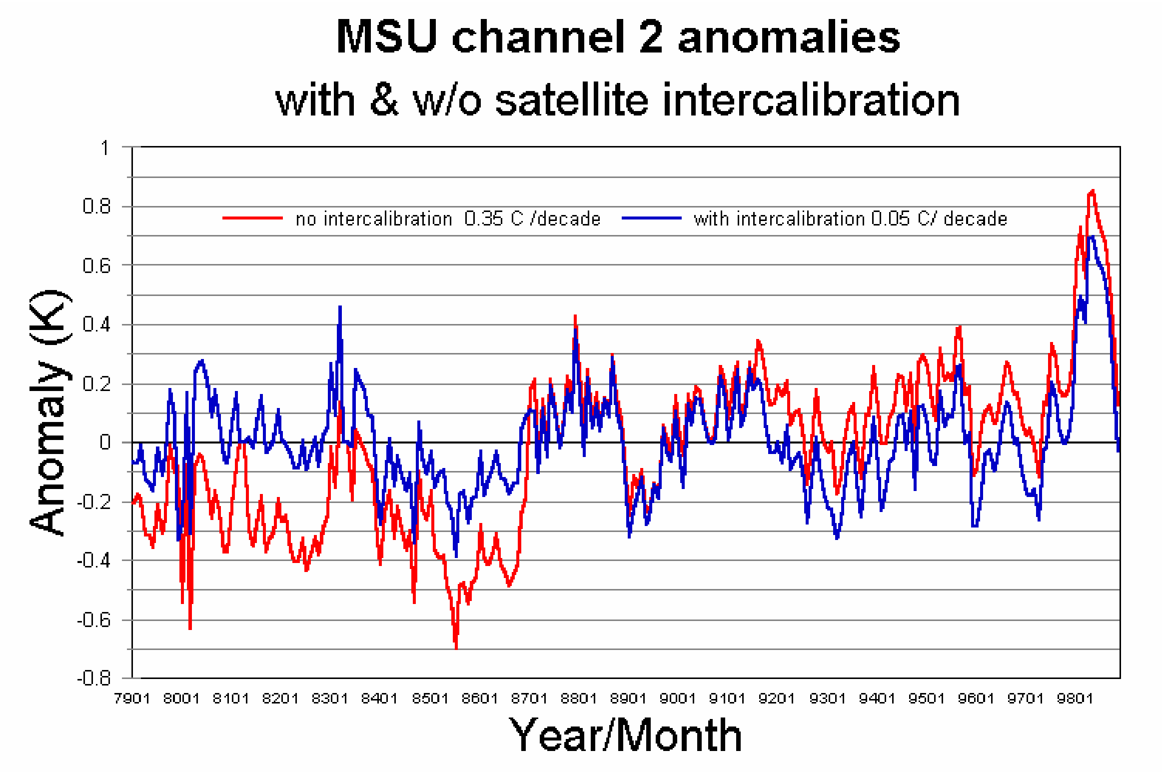

Figure 3-4. Impact of MSU Channel 2 Intercalibration on Global Trends

Source: http://www.ghcc.msfc.nasa.gov/ghcc.cvcc.html

3.2.3 Vicarious Calibration

Ultimately, we should strive to have an international standard, such as we have for weights, lengths, and time, for satellite radiometers and other space-based instruments. The stringent engineering criteria to perform such an absolute calibration, however, are not achievable with current instrumentation. Thus, we are left to use a variety of ad hoc means for attempting to absolutely calibrate satellite instruments. These techniques can involve underflights with similar test instruments, calibration against in situ measurements of geophysical variables, and calibration against ground targets of known value. In this case, the application of the GCOS 11th principle, multiple independent observations and analysis techniques for critical climate variables, applies. The following figure shows the adjusted AVHRR visible channel using the Libyan Desert as a vicarious target. The AVHRR has no on-board nominal calibration, so vicarious calibration is needed to construct a stable time series.

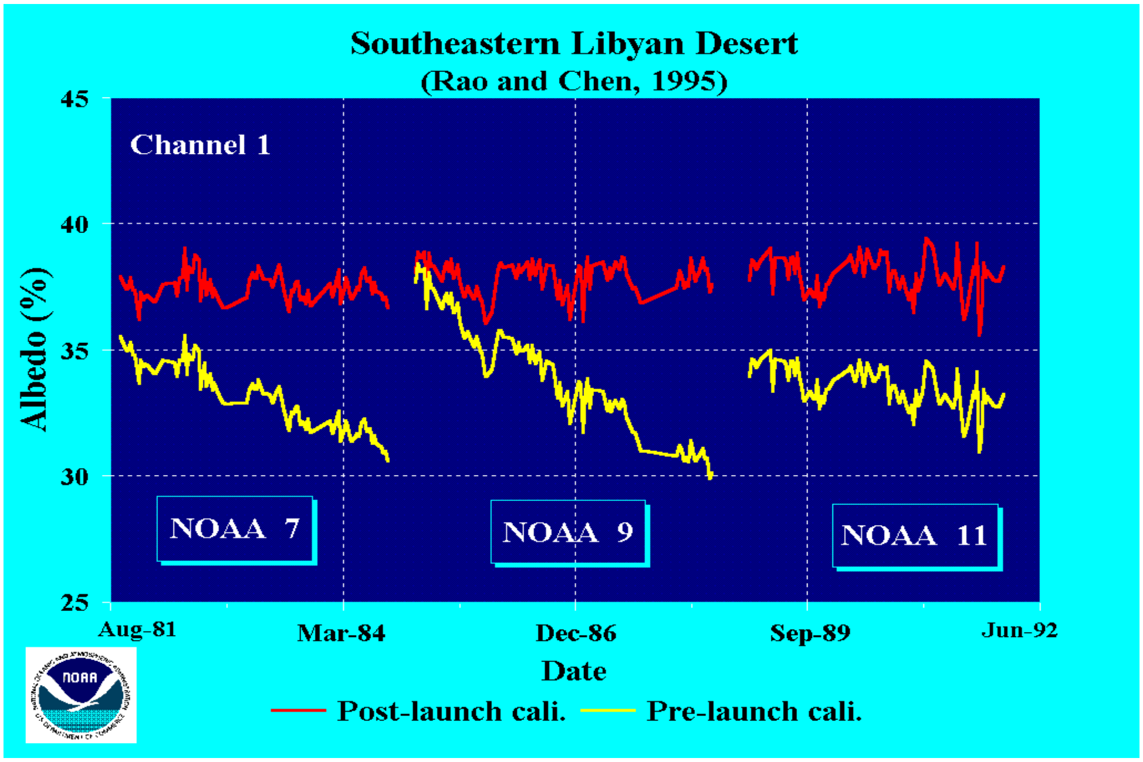

Figure 3-5. Example of Vicarious Calibration

3.3 Expect the Unexpected

Experience with the operational satellite data of the past nearly 25 years of data has also shown that observing the Earth from space is subject to the vagaries of nature. A most important lesson was gained shortly after the launch of the first AVHRR/2 instrument in 1982. Prior to that time, efforts to accurately estimate the sea surface temperature from space-based observations were plagued by corrections required to remove the effects of atmospheric water vapor. The selection of multiple infrared window channels on the AVHRR/2 was optimized to allow for correction of this water vapor effect by using dual window channels with differential sensitivity. One could use the differential sensitivity to extrapolate to zero water vapor absorption and, hence, obtain a highly accurate SST. The eruption of the El Chichon volcano in southern Mexico, however, sent large quantities of volcanic aerosols into the stratosphere. These aerosols acted radiatively opposite to the water vapor absorption correction in the dual channels, thus negating the ability of the AVHRR/2 to accurately correct for water vapor absorption. The eruption of the Mt. Pinatubo volcano in 1991 had an even larger effect and also made it impossible for the Stratospheric Aerosol and Gas Experiment (SAGE-II) instrument on the NASA research satellite to retrieve the quantities it was designed to measure. The lesson is that one should never become reliant on a single observation for a critical climate variable.

The next figure shows the impact of Mt. Pinatubo on the SST anomaly. The top panel shows the large negative anomalies due to contamination. The middle panel is SST anomaly after the SST algorithm was modified to include an aerosol correction. The third panel is NESDIS/CPC blended SST product (NCEP Reynolds) which is used for comparison.

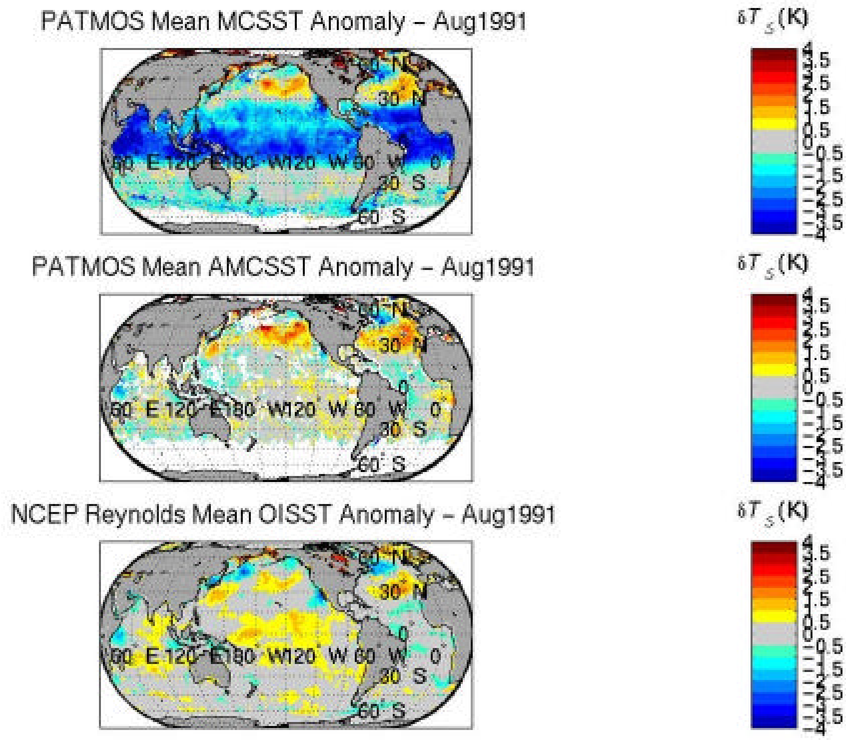

Figure 3-6. SST Anomaly without Aerosol Corrections (top panel), with Correction (middle panel) and Comparison with the NCEP Reynolds SST.

Source: NESDIS/ORA

4 Where Are We Going?

To provide a framework to ensure that satellite climate data are processed, archived, and distributed to users in a manner that is scientifically defensible for monitoring, diagnosing, understanding, predicting, modeling, and assessing climate variation and change.

NOAA manages the nation's civil operational environmental satellite system. NOAA also has statutory responsibility for long-term archiving of the nation's environmental data. Increasingly, this responsibility is expanding to provide information on the health of the environment in real-time to both national and international users, and to respond to growing demands for stable long-term climate records derived from satellite observations. In order to meet these needs, NOAA must provide a framework to ensure that satellite climate data are processed, archived, and distributed to users in a manner that is scientifically defensible for monitoring, diagnosing, understanding, predicting, modeling, and assessing climate variation and change.

As concern for understanding climate change and variation has grown, it has become apparent that the somewhat *ad hoc* nature of adapting observations originally intended for weather prediction to climate study (as described in Sections 2 and 3 of this report) is not sufficient to produce reliable findings and draw reasonable conclusions. While real-time operational products from NOAA's space and ground-based environmental observing systems meet the goals for short-term environmental forecasting and stewardship, they have not generally become authoritative long-term records.

NOAA's acceptance of its role and responsibilities for providing quality climate data is reflected in NOAA's Strategic Plan for FY2003 – FY 2008 and Beyond, "New Priorities for the 21st Century":

> "To enable society to better respond to changing climate conditions, NOAA, working with national and international partners, will employ an end-to-end system comprised of integrated observations of key atmospheric, oceanic, and terrestrial variables; a scientific understanding of past climate variations and present atmospheric, oceanic, and land-surface processes that influence climate; application of this improved understanding to create more reliable climate predictions on all time scales; and service delivery methods that continuously assess and respond to user needs with the most reliable information possible."

NOAA recognizes that the development of quality climate data records is key, and that a strong program focus on the development, retention, and distribution of climate data records will be necessary to meet the needs of researchers and decision makers. In short, NOAA must "operationalize climate."

4.1 Users Needs

4.1.1 Climate Data Users

Users of climate data include organizations both within and outside the NOAA and NASA communities. Some of the primary user communities include:

- NOAA's Climate Prediction Center and NOAA Line Offices
- NOAA, NASA, other agency and academic researchers
- Federal government agencies with environmental stewardship, disaster planning, national defense, homeland security, and land use responsibilities (EPA, NOAA, FEMA, DOD, DOI)
- State and local officials responsible for disaster planning and natural resource protection
- International governments and organizations
- The public

4.1.2 Uses of Climate Data

Simply put, climate data users seek information to:

- Assess the current state of climate
- Assess changes in climate
- Predict future climate change
- Verify climate models
- Understand the processes controlling climate

Climate change and variation occur over a range of time scales and therefore climate data must be collected over a time series in order to be able to detect and understand these changes. The concepts of climate change and variability include both short-term and long-term components. The short-term component (generally called *climate variability*) includes seasonal changes, multiyear extended periods of wet and dry conditions (prolonged periods of above normal hurricane activity, excessive rainfall or drought) and the periodic cyclical changes through wet and dry conditions that occur generally within a 20-year time frame. Such changes may be related to global events, but effects at the regional level (e.g. the West Coast of the United States) may differ from the response in some other region (the East Coast). The long-term component (generally called *climate change*) refers to more or less permanent changes that occur over a longer period and have global implications. The result is an overall trend that has impacts throughout the world. These include phenomena such as increased concentrations of carbon dioxide in the atmosphere and changes to the ozone layer.

Public and private sector decision makers need to consider the effects of *climate variability* in planning and making day to day decisions concerning operations, maintenance, and activity scheduling. They also need to consider *climate change* for long-term planning, design and construction of infrastructure, as well as associated needs to protect natural resources, lives and property.

Both climate change and variability are occurring simultaneously, so that effects are additive and cumulative over time. To provide maximum flexibility, climate data need to be observed and collected over a range of temporal and spatial scales not generally used for weather prediction. Generally, three time scales apply and differ in their accuracy requirements.

- *Real-time, subseasonal to seasonal*
  Seasonal fluctuations in environmental variables such as precipitation or temperature can be very large.
- *Seasonal to interannual*
  The variability in observations for seasonal to interannual scales is smaller than for real-time fluctuations, so the requirement for accuracy increases significantly. For example, El Niño is a climate phenomenon characterized by periodic warming of sea surface temperatures across the central and east-central equatorial Pacific. An El Niño episode may be declared when a 3-month average of sea surface temperature readings increases 0.5ºC.
- *Decadal to centennial for measuring trends*
  Climatic trends are measured over this time scale. The need for accuracy is an order of magnitude greater, and subtle features in climate trends and variability can only be detected in the longest geophysical records. Global temperature change over a decade is approximately 1/10 of a degree.

In order to describe, understand, and predict what is happening to earth system processes, climate variability and change need to be monitored and tracked an a global and ongoing basis. The potential for satellite observations to contribute to this body of knowledge has been recognized, but has not been fully utilized because the data have been collected and formatted primarily for weather applications.

4.2 Conceptual Framework

The need to monitor and track climate variability and change on a global and ongoing basis was recognized by the CCSP and is reflected in six overarching goals in the Observing and Monitoring the Climate System chapter of the CCSP Strategic Plan:

Goal 1:	Design, develop, deploy, and integrate observation components into a comprehensive system.
Goal 2:	Accelerate the development and deployment of observing and monitoring elements needed for decision support.
Goal 3:	Provide stewardship of the observing system
Goal 4:	Integrate modeling activities with the observing system
Goal 5:	Foster international cooperation to develop a complete global observing system.
Goal 6:	Manage the observing system with an effective interagency structure.

To promote full exploitation of the scientific value of satellite data by current and future users, and to meet the goals of the CCSP strategic plan for monitoring and observing the climate system, five functional activities must be put in place and programmatically managed by

NOAA. The program should be structured around an end-to-end process focusing on the following:

- Observing system performance monitoring
- Near real-time CDR generation
- Processing and analysis of CDRs
- Research and applications
- Archiving and distributing the data record

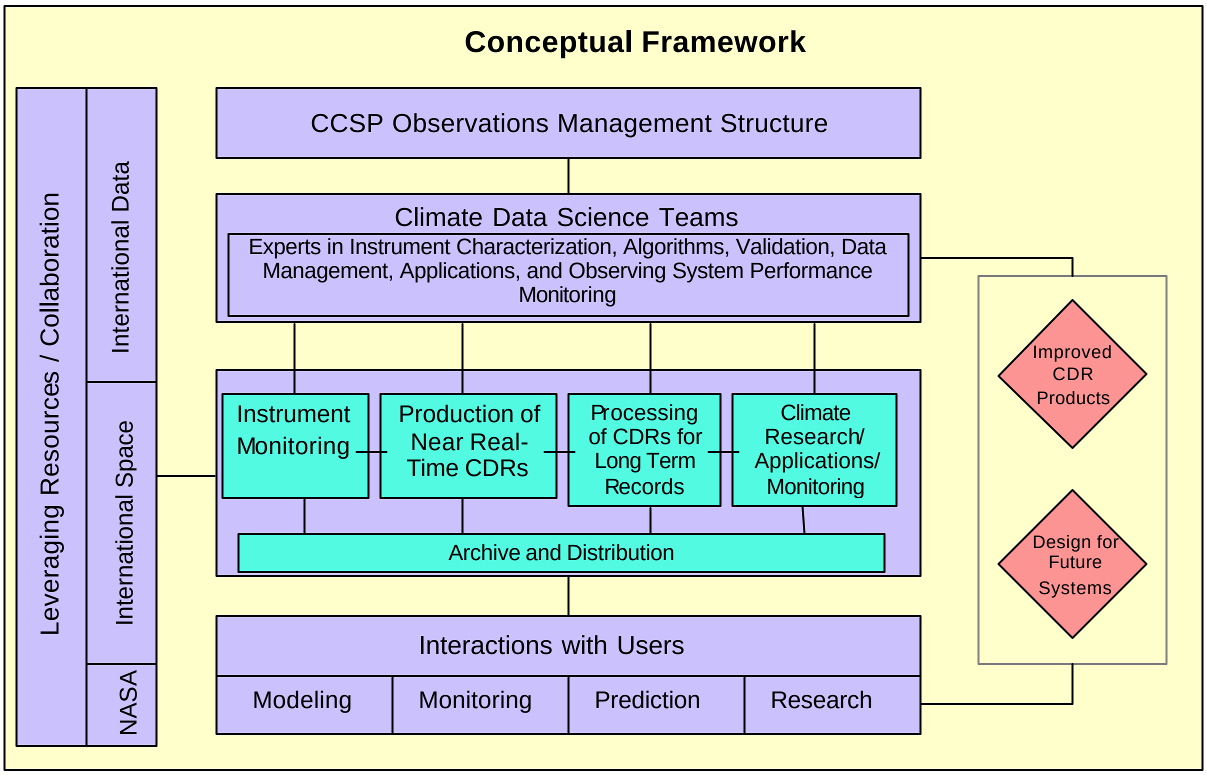

Figure 4-1. Conceptual Framework for Creating Climate Data Records

4.2.1 Observing System Performance Monitoring

The first function of an end-to-end system for climate data records is to provide real-time monitoring of the observing system performance. Providing data whose quality is known and for which temporal and spatial biases are minimized begins with understanding the effects of the observing system on the data. NOAA's current satellite instruments (except for SBUV ozone sensors) were designed to collect data mainly for weather observations, not for study of small, long-term changes in climate. The construction of long-term data sets must address several characteristics of satellite data.

Satellite observing system factors affecting the data quality include the following:

- Biases inherent in the observing instrument
- Changes in instruments

- Satellite orbital drift
- System calibration
- Sensor degradation in space
- Satellite to satellite discontinuities
- Satellite or instrument system malfunctions

Measurements can be significantly compromised by changes, both intentional and unintentional, in instruments and measurement practices over time. These changes sometimes produce system perturbations to the measurements such that long-term trends computed from these data are subject to considerable uncertainty. For example, satellite observations for detecting atmospheric temperature trends have been affected by the gradual drift of the time of the day that a NOAA POES satellite actually views an area. This orbital drift can result in a false trend that is not caused by a change in climate, but is due to the changing time of the observation. Not only does the behavior of the satellite create an artificially induced reading, the reported data may be hiding signals of actual changes in climate variables. Recognizing and correcting for the false trend in the data allow detection of the actual climate trend, and creation of an adjusted, validated climate data record that can be used in combination with other climate data records. Observing system performance monitoring will require the development of tracking and assessing tools to detect and account for changes in the observing system as well as in the observation record. In addition, a proactive approach will be needed to assess the impact of new systems or changes to existing systems before they are implemented, so that data continuity requirements are taken into account. Introduction of a different satellite or instrument will inevitably create changes in instrument or measurement bias. As changes in the observing system take place, NOAA will need to anticipate the impacts to the long-term data record.

NOAA has proposed a number of activities for POES observing system performance monitoring, which will fill in some data gaps and provide basic tools for system monitoring:

- Inventory data, fill in missing periods to capture all data that exist anywhere in NOAA archives
- Convert internal satellite quality information into useful products for end-users
- Provide easy web-based tools to link end user QC information to more detailed instrument information
- Build and provide tools to read Level 1b data[17]

For NPOESS, activities planned for observing system performance monitoring focus on building an infrastructure using common tools. The goals will be to:

- Adopt HDF 5 as a common standard for CDRs
- Put thinned, raw data sets in common grids
- Adopt and provide metadata standards

4.2.2 Near Real-Time CDR Generation

The second function of the end-to-end process is to establish a capability to generate CDRs in near real-time. Generally speaking, an EDR must be generated within a few hours. For a

[17] See Section 2.2.4, footnote 14.

CDR, the time constraints are not hourly, but daily, weekly, or monthly depending on the application. A major objective of this function is to maximize the benefit of using *routine observations* from existing and emerging operational observing programs for climate studies.

A comprehensive, operational capability to generate CDRs will allow routine and continuous use of satellite remote sensing data for prediction of climate variability, such as the ENSO, extreme storm events, excessive rainfall or drought. In addition, near real-time CDRs can be used to develop data sets that can be compared with or added to the historic record to provide long-term climate monitoring or to contribute to climate research. As data are received, scientists at NOAA will automatically update historical climate data bases to maintain a global climate perspective in near real-time.

Creation of CDRs will require program components in:

- Calibration, inter-calibration and characterization of satellite instruments
- Development of processing algorithms
- Detection and elimination of systematic errors in the data set
- Generation of stable climatic time series
- Validation of data products
- Analysis of data

Converting the raw data records, sensor data records, and EDRs to produce CDRs and science products will be a major challenge. NOAA envisions that the scientific community will be involved in the definition and development of the algorithms used for processing science data products. These algorithms will be used to process the data from the lowest level satellite data to create high quality science data products. NOAA researchers and the science community will need to develop methods for combining data output from different sources as well as new analysis and assimilation techniques. The climate record is particularly sparse for ocean related measurements and variables. Involving mission-oriented agencies such as FEMA, DOI, COE, and USDA will help identify research needs.

The lessons learned from previous, successful CDR generation programs will be used to establish a framework that ensures:

- A tight connection between the algorithm developer and the CDR generator (which could be the same group)
- A strong calibration/validation program
- Development of climate data products by scientist who have direct knowledge of the research requirements, by involving them in programmatic research activities.
- Collaboration with user communities

As the NOAA plan for creating climate data records moves forward, the following essential questions should be addressed:

- What are CDRs and how do they differ from EDRs?
- How does a CDR become a community standard (established as legitimate)?
- How can NOAA ensure that the CDRs are responsive to user needs?

- What are the key attributes of successful CDR generation programs?
- What are the advantages and disadvantages of different models or strategies for producing CDRs, such as using partnerships among government, academia, and the private sector, different blends of space-based and in-situ data (e.g., all space-based versus some balance) or other approaches?
- How can NOAA learn from present and past efforts such as the NOAA/NASA Pathfinders, EOSDIS, and so on? What are the successes and failures, and how does NOAA build on the successes to avoid the pitfalls?

4.2.3 Processing

The third component of the end-to-end system is to ensure the long-term value of the authoritative data record to assess the current state of the environment and to put it in historical perspective. As CDRs are archived and become part of the historic climate record, the utility of these authoritative records will need to be preserved and enhanced by conducting rigorous data analysis and reprocessing. Periodic reprocessing of data sets will be necessary to identify and resolve problems in the data, create and combine new data sets, and incorporate improved algorithms or new scientific findings.

Using CDRs generated in near real-time for long-term climate studies can be a complex undertaking because combining them into a long-term record may create inconsistencies or incompatibilities resulting from shifts in methodology or observing systems. Biases and errors related to the satellite, the observing instrument, or data collection methods are set in time. As the understanding of sensor calibration issues and radiative transfer from Earth advances, data processing algorithms will be improved and better climate data sets and products can be generated. It is expected that processing will become a routine activity at regular intervals, perhaps every few years, as algorithms for adjusting the data are developed.

Periodic re-analysis of the long-term data record may be called for when:

- *An improved algorithm is developed*
  Data will be reprocessed to accommodate the latest scientific findings into the data products. As scientific research improves our understanding of the earth's physical processes, existing algorithms will be refined or replaced with new algorithms.
- *New information on the in-flight behavior of an instrument comes to light*
  Analysis of instrument behavior may result in recalibration of the sensor measurements.
- *An error is discovered in a processing system*
  A coding or other software error may be discovered in the processing system. This type of error may not be detected in an EDR, but analysis and comparison with other data sets might reveal an error at the CDR level.

It is anticipated that NOAA, in collaboration with science teams, will perform ongoing data analysis and processing to update the data record as systematic errors or biases are discovered and as new algorithms or scientific findings are introduced. The processing of data must be accompanied by documentation of the production characteristics and quality control of the production process.

4.2.4 Research and Application

Another component of the end-to-end system involves a research activity, as opposed to the "housekeeping" responsibility of processing data sets. With the participation and guidance of the science community, NESDIS will work with the long-term data record to continue to make contributions to climate variability and change research by analyzing data sets to uncover trends. Activities will include the following:

- *Development of Climate Quality Algorithms for Creating CDRs*
  Processing algorithms to transform satellite observed radiances into geophysical variables do not appear out of thin air. An ongoing algorithm development program is needed to advance the science of remote sensing.
- *Analysis of Time Series*
  NESDIS and climate science teams will review time series of CDRs and interpret the data in terms of what trends are emerging from the data record. This analysis will add to the climate science by evaluating what the data are showing and comparing it to what other researchers have found. The analysis may also find errors indicating the need to process a particular data set.
- *Joint Studies with the Climate Modeling Community*
  The primary purpose of this activity is to evaluate and verify existing climate models. These studies may also lead to the establishment of boundary conditions or initial conditions for climate models.
- *Assessments*
  NESDIS and science teams will digest information from the climate data record, develop data sets, and publish periodic assessments for use by decision makers, other climate researchers and the public. These assessments will be "published" and disseminated across a range of media including the internet. One example of this type of assessment is the annual climate review disseminated by NCDC. Such a report may present an annual assessment of global temperatures and precipitation, U.S. temperature and precipitation summaries, significant events, the Atlantic Hurricane Season, and the Western U.S. Wildfire Season.

4.2.5 Archiving and Distributing the Data Record

Ensuring complete archival and access capabilities, the final function of the end-to-end system, requires a continuing commitment to the establishment, maintenance, validation, description, accessibility and distribution of quality long-term data sets. Metadata, direct observations, and fundamental records from satellite and in situ platforms must be comprehensive, complete, and preserved in perpetuity. Federal policy mandates full and open access to data for climate change research. Open, efficient access to the metadata, products, and data streams must be ensured, and data made available in useful formats.

4.2.5.1 Archiving

Preservation of all data will be required. Documentation must include clear, concise descriptions of the data, its source and processing history. Documentation will include the scientific algorithms used to process the data and a description of the processing steps and ancillary data used in its production. Decisions as to which data should be preserved should be made in coordination with the scientific community.

The Archive content will include, but is not limited to the following:

- Data
- Metadata
- Production software source code
- Software to read the data
- Documentation on data, metadata and formats
- Ancillary data
- Calibration/Validation information and data
- QA information

NOAA, working with climate researchers, will define and maintain science-approved standards and guidelines for data archiving, consistent with the expectations and practices of the science community. Internationally agreed standards should be used for data acquisition, processing, archiving and distribution to the extent possible. Standards will be developed for metadata, read software, and documentation.

To accommodate advances in storage technology, NOAA must have the ability to migrate the data to different archive media. Having data trapped on unsupported or obsolete technology must be avoided to ensure archive viability. When possible, NOAA will avoid proprietary software environments that limit flexibility in system development and maintenance. Use of open source solutions will optimize flexibility and possibly lower costs. NOAA should plan for archive technology upgrades and insertion on a 3-5 year cycle, and be continuously alert to the possibility of data sets suddenly becoming vulnerable. Integrity checks must be performed on archive media between data migrations.

Regular, periodic backup of all data and information held in the archive will be performed to preserve the data for future use. NOAA will provide an off-site backup copy of all data and information that is held in the archive.

Resource constraints may require that some data sets are relegated to passive but safe storage, and that some data sets are eliminated from the inventory. NOAA will need to prioritize data holdings and involve the scientific community in the prioritization process.

4.2.5.2 Access

A critical objective for the end-to-end system is to provide the free and open sharing and exchange of climate related data and products. Much of the data will need to be made available in near real-time so that it can be assimilated into models to provide physically relevant variables. Other data may be made available only after a period of time necessary to ensure quality control.

Users will have affordable and relatively easy access to raw radiances as well as to science products. The goal will be to ensure not only that climate data are captured, quality controlled, archived and distributed; but that global data products using the climate data record are produced and distributed to the climate community at large. Community consensus algorithms and techniques will be sought to accomplish these goals. Standards will be developed for the data and media format to be supported for data distribution.

As analysis continues to improve and strengthen the climate data record, new data sets will be made available for use by the climate research community. Scientists will have access to improved data sets as well as better understanding of its strengths and weaknesses. Permanent archiving of key data sets to support the long-term global record will include data maintenance, and the maintenance of data formats, documentation, read software, and the science data product generation software, to permit access to the data in the future. Data manipulation and visualization tools to serve the broader science community will also be developed.

NOAA will seek to gain an understanding of the ways and extent to which customers have access to hardware, media devices and the internet to provide rapid data delivery at minimal cost.

To improve efficiency of access, NOAA will periodically evaluate the organization of data sets in the archive, in light of actual user access and data usage patterns.

4.3 Summary: Discussion Issues on the Development of a Plan for Creating Climate Data Records from NOAA Operational Satellites

The functional areas and key attributes of a high quality end-to-end system for satellite-based climate data, as described in earlier parts of this section are listed below:

Functional Areas

- Observing system performance monitoring
- Near real-time CDR generation
- Climate processing
- Research and applications
- Archiving and distributing the data records

Key Attributes of Successful CDR Programs

- A tight connection between the algorithm developer and the CDR generator (may be the same group)
- A strong calibration/validation program
- Research with the data set as part of the program
- Collaboration with user communities (e.g., diagnosticians, modelers) to generate feedback
- Science oversight

To ensure that CDRs are both accessible and useful to climate researchers and decision makers, and to promote science community participation and consensus, NESDIS is seeking advice from the National Academies on the following issues prior to developing a NESDIS plan for creating climate data records from NOAA satellites.

Science Oversight and Participation by External Community

Many successful CDR programs have included participation by the science community in one way or another. These may take the form of instrument oriented science teams, such as the NASA instrument teams or the NOAA/NASA Pathfinder teams, or product oriented teams, such as those associated with the WCRP/GWEX ISCCP and GPCP programs. In some cases, team members are funded to work on problems associated with the CDR program, in other cases they serve in purely advisory capacity. Team members have been selected in different ways:

- In response to an open competition
- Appointed by their agencies
- By volunteering

Examples of functions that could be carried out in this way include: algorithm development, generation of CDRs (for the smaller data sets), validation campaigns, research with the data set, and evaluation of the data in climate models or other applications.

The issues are: What approach should NOAA consider for obtaining science guidance and oversight for its end-to-end CDR program? What scientific criteria should be used to decide whether a function should be performed in-house or externally?

The NOAA-NASA Relationship

As the NPOESS program evolves, and extends many of the climate observations begun under NASA's EOS program, the generation of long-term, high-quality CDRs will become a high priority NOAA mission. However, because of NASA's expertise and great interest in obtaining the best possible satellite-based climate data sets for research, it seems natural that NOAA explore formal cooperation possibilities with NASA as part of NOAA's plan for creating CDRs from NOAA satellites. NOAA and NASA have a history of cooperative activities related to CDR generation, including the NOAA/NASA Pathfinder program, the joint NOAA and NASA support of development of data sets for NOAA's Climate Change Data and Detection project, NOAA scientist participation on NASA science teams that produce CDRs, and the NOAA/NASA cooperation on the generation of a long-term ozone data.

The issues are: What are some realistic options for engaging NASA in an end-to-end system for generating CDRs from the operational satellites?

Obtaining Feedback from Users

It is extremely important that NOAA obtain feedback from the user community on the utility of the CDRs in the various climate applications—climate monitoring and diagnosis, seasonal to interannual climate prediction, decadal scale climate modeling, climate research, and other governmental and private sector applications. Only in this way will NOAA be able to evaluate the benefits of its investment in the program and be more responsive to the user community.

The issues are: What are the optimal mechanisms for entraining the user community in the use, test, and evaluation of CDRs and for obtaining feedback?

Participation in International Data Projects

Some of the widely used satellite climate data sets have been produced as part of international programs, in particular, the WCRP. To the extent that these programs use operational satellite data and are intended to provide a sustained, long-term record, it seems appropriate for NOAA to actively participate in such programs. NOAA already participates in the ISSCP by funding of satellite data collection and sampling, and serving as the central ISCCP archive. A NOAA scientist is the manager of the GPCP and NOAA produces SSM/I rainfall data for the project.

The issues are: What should be the role of NOAA in international data projects? What functions should NOAA perform?

Algorithm Selection

To obtain the best possible climate data set, one should use the best available processing algorithm. Algorithms have been selected in various ways. For NOAA's satellite EDRs, in-house Product Oversight Panels evaluate and approve algorithms developed by in-house scientists. Other data generation programs have conducted algorithm 'bake-offs" to compare and select algorithms for CDR production. A single two-man team developed the algorithm for one of the most widely used CDRs – the MSU atmospheric temperature data set.

The issues are: What are some viable approaches for algorithm selection? Once an algorithm is implemented, what procedures should be used to determine if a new algorithm should be replaced? How should replacement algorithms be selected?

Summary

In summary, NOAA's vision is that through the establishment and execution of an end-to-end system for CDRs, more confident conclusions may be drawn regarding climate variability and change, and that this improvement will benefit policy makers and the public at large. By establishing a programmatic framework to properly address issues surrounding climate data records, NOAA will ensure the quality, usefulness, and accessibility of the data for current and future generations.

Appendix A - NRC Recommendations Relevant to Creating CDRs

NRC Category	NRC Recommendation	NRC Source (see master list below)
Climate observing requirements	Build climate observing requirements into the operational programs as a high priority.	Adequacy of Climate Observing Systems
Climate research programs	Revamp climate research programs and some climate-critical parts of operational observing programs.	Adequacy of Climate Observing Systems
Climate-specific observational programs	Establish a funded activity for the development, implementation, and operation of climate-specific observational programs.	Adequacy of Climate Observing Systems
Critical variables	Identify critical variables that are either inadequately or not measured at all.	Adequacy of Climate Observing Systems
Observational capability	Stabilize the existing observational capability.	Adequacy of Climate Observing Systems
Existence of a long-term observing system	Ensure the existence of a long-term observing system that provides a more definitive observational foundation to evaluate decadal- to century-scale variability and change.	Climate Change Science
Observation system components	The observation system must include observations of key state variables such as temperature, precipitation, humidity, pressure, clouds, sea ice and snow cover, sea level, SST, carbon fluxes and soil moisture.	Climate Change Science
Regional measurements of greenhouse gases	More comprehensive regional measurements of greenhouse gases would provide critical information about their local and regional source strengths.	Climate Change Science
Basic set of user services and tools	NOAA and NASA should define and develop a basic set of user services and tools to meet specific functions for the science community, with NOAA assuming increasing responsibility for this activity as data migrates to the long-term archive.	Ensuring Climate Record
Blend of distributed and centralized data and info services	NASA and NOAA should develop and support activities that will enable a blend of distributed and centralized data and information services for climate research.	Ensuring Climate Record
Development and evaluation of CDRs	NASA, in cooperation with NOAA, should support the development and evaluation of CDRs, as well as their refinement through data processing.	Ensuring Climate Record
Large-volume data access	NOAA should guarantee climate researchers affordable access to all RDRs in the long-term archive, with an emphasis on large-volume data access.	Ensuring Climate Record
Long-term archiving and NPP data system prototypes	NOAA, in cooperation with NASA, should invest in early, limited capability prototypes for both long-term archiving and NPP data system.	Ensuring Climate Record
NPOESS Preparatory Project	NASA, in cooperation with the Integrated Program Office, should develop the NPOESS Preparatory Project as an integral component of a climate data system.	Ensuring Climate Record
Preserve in perpetuity basic satellite measurements	NOAA should begin now to develop and implement the capability to preserve in perpetuity the basic satellite measurements.	Ensuring Climate Record

NRC Category	NRC Recommendation	NRC Source (see master list below)
NASA Earth Science Enterprise's active role	The NASA Earth Science Enterprise should continue to play an active role in the acquisition and analysis of systematic measurements for climate research as well as in the provision of new technology for NPOESS. NASA/ESE should ensure the systematic measurements that are integrated into operational systems continue to meet science requirements. NASA/ESE should continue satellite missions for many measurements that are critical for climate research and monitoring.	Integration I
Use of NPOESS for climate research and monitoring	The Integrated Program Office for NPOESS should give increased consideration to the use of NPOESS for climate research and monitoring. For those NPOESS measurements that are deemed to be critical for climate research and monitoring, the IPO should establish a science oversight team with specific responsibilities for each associated sensor suite. The IPO should begin to establish plans for sensor calibration and data product validation as well as for data processing and delivery that consider the needs for climate research.	Integration I
Active microwave sensors	Proven active microwave sensors should be considered for ocean vector winds, another key climate (and operational) parameter.	Integration II
Calibration of thermal sensing instruments	Calibration of thermal sensing instruments such as CERES (Clouds and the Earth's Radiation Energy System) and the thermal bands of MODIS (Moderate-resolution Imaging Spectroradiometer) should continue to be traceable to the SI unit of temperature via the Planckian radiator, blackbody technology.	Integration II
Establishment of traceability	The establishment of traceability by national measurement institutions in addition to the National Institute of Standards and Technology should be considered to determine if improved accuracy, reduced uncertainty in the measurement chain, and/or better documentation might be achieved, perhaps even at a lower cost.	Integration II
Free-flier status	Free-flier status should be evaluated for key climate parameters such as solar radiance and sea-level altimetry whose measurement appears to be endangered by the NPOESS single-platform configuration.	Integration II
Long-term archiving system	A long-term archiving system is needed that provides easy and affordable access for a large number of scientists in many different fields.	Integration II
Metadata documentation	Data should be supported by metadata that carefully document sensor performance history and data processing algorithms.	Integration II
Planning for a research-oriented NCDS and the associated science participation	The research community and government agencies should take the initiative and begin planning for a research-oriented NCDS and the associated science participation.	Integration II
Quality assessment	Quality assessment should be an intrinsic part of operational data production and should be provided in the form of metadata with the data product.	Integration II

NRC Category	NRC Recommendation	NRC Source (see master list below)
Radiometric characterization of the moon	Radiometric characterization of the Moon should be continued and possibly expanded to include measurements made at multiple institutions in order to verify the NASA results. If the new reflectance calibration paradigm is adopted, then the objective of the lunar characterization program should be to measure changes in the relative reflectance as a function of the phase and position of Earth, the Sun, and the Moon rather than absolute spectral radiance.	Integration II
Reprocess large data sets	The system should have the ability to reprocess large data sets as understanding of sensor performance, algorithms, and Earth science improves. Examples of sources of new information that would warrant data reprocessing include the discovery of processing errors, the detection of sensor calibration drift, the availability of better ancillary data sets, and better geophysical models.	Integration II
Results of sensitivity studies on the parameters in the data product algorithms	The results of sensitivity studies on the parameters in the data product algorithms should be summarized in a requirements document that specifies the characterization measurements for each channel in the sensor. Blanket specifications covering all channels should be avoided unless justified by the sensitivity studies.	Integration II
Selection of instrument science teams	Competitive selection of instrument science teams should be adopted to follow the progress of the instrument from design and fabrication through integration, launch, operation, and finally, data archiving, thereby promoting more thorough instrument characterization.	Integration II
Selection of science teams	Science teams responsible for algorithm development, data set continuity, and calibration and validation should be selected via an open, peer-reviewed process (in contrast to the approach taken with the operational integrated data processing system (IDPS) and algorithms, which are being developed by sensor contractors for NPOESS).	Integration II
Validation of each product and record	Validation, an essential part of the information system, should be undertaken for each data product or data record to provide a quantitative estimate of the accuracy of the product over the range of environmental conditions for which the product is provided.	Integration II
Communicating instrument performance	NESDIS should create a web site that includes information on spacecraft and instrument condition and changes that are of interest for the construction of CDRs. In addition to the official NESDIS TIROS Operational Anomaly Reports (TOAR), this site should be interactive to allow climate investigators to communicate their findings and opinions concerning the behavior of specific instruments and/or channels. The site should be well organized, with cross-referencing by category, and should include a good search capability to enable interested parties to find what they want. An attempt should be made to hierarchically construct the site so that issues judges by NESDIS to be of greatest importance to the climate record are most prominently featured. The information contained on this web site would become part of the permanent metadata record for each instrument.	Letter Report, September Reconciling Temperature Observations
Continued production of remotely-sensed stratospheric CDRs	NESDIS should take responsibility for the construction and validation of CDR-quality bulk-layer temperature time series from the SSU and AMSU for the analysis of stratospheric climate variations and trends.	Letter Report, September Reconciling Temperature Observations

NRC Category	NRC Recommendation	NRC Source (see master list below)
Inclusive dialogue/information exchange	NESDIS should establish for each POES operational instrument a structure by which the communication of information may be assured as CDRs are developed and refined. This could be implemented wit the establishment of an ad hoc group of individuals who are involved in some way with the development of the instrument and the CDRs. Sponsored meetings or workshops, possibly with published proceedings, would help ensure that the right mix of people have access to one another. Another approach could be the formal establishment of, for example, an MSU/AMSU Climate Science Team which would afford the members the opportunity to deal with issues of calibration, validation, long-term stability, and future requirements for deep-layer atmospheric temperature (as well as other microwave-based products). The team could also advise NESDIS/NCDC on issues of data storage, data access, and which significant products to archive.	Letter Report, September Reconciling Temperature Observations
Network performance monitoring	A network performance monitoring system to identify both random errors and time-dependent biases in both space-based and in situ observing systems would enable NOAA and the scientific community to identify and correct errors as soon as possible in these critical observing systems. These diagnostics should become part of the metadata associated with the observations.	Letter Report, September Reconciling Temperature Observations
NOAA's Climate Mission	NOAA should reinvigorate its efforts to "ensure a long-term climate record" (NOAA, 1995). This perspective should permeate the full range of activities related to climate observation, including instrument design and specification, instrument siting, specification of observing methods, data and metadata archiving, production and validation of CDRs, data analysis, and dissemination of products.	Letter Report, September Reconciling Temperature Observations
Production of CDRs	NOAA should take responsibility for identifying proven CDRs and ensuring that the construction of these be maintained. In addition, NOAA should assume responsibility for supporting and developing the required scientific expertise, documenting the CDR construction methodology, and ensuring that the scientific expertise has been institutionalized, rather than merely residing with individual scientists. It is also important that the time series can be reproduced by future investigators.	Letter Report, September Reconciling Temperature Observations
Sensor calibration	NOAA should put a high priority on measuring all aspects of the radiometer's system gain function and baseline offset during pre-launch testing. The usual set of thermal-vacuum tests should be expanded and done more rigorously, and the test results should be made readily available to the scientific community for evaluation. Since the calibration drift seems to be related to temperature, a sufficient number of precision thermistors should be mounted on the various radiometer components (antenna, feedhorn, front-end receiver, detector, etc.) for on-orbit monitoring and drift detection. More robust on-board calibration systems (e.g., additional reference loads) should be considered for future missions.	Letter Report, September
Assessment on the effects on long-term climate monitoring	Prior to implementing changes to existing systems or introducing new observing systems, an assessment on the effects on long-term climate monitoring should be standard practice.	LTA
Diurnal sampling biases	For polar orbiting satellites minimize the aliasing of the diurnal cycle of the parameter of interest, and most importantly ensure that diurnal sampling biases do not change with time by controlling the flight of the orbiting satellite.	LTA

NRC Category	NRC Recommendation	NRC Source (see master list below)
Existing and new information management systems	Improve existing and develop new information management systems related to the gathering, quality control, assembly, and archiving of climate data; and a system of telemetry, communication, and permanent storage dedicated to the objectives of the system.	LTA
Historical data base	Continued efforts should be made to improve the quality and volume of the historical data base, including long-term high resolution data capable of resolving important extreme climate events.	LTA
International exchange of data	Ensure that the full and open international exchange of data is maintained at minimal cost of reproduction.	LTA
Long-term climate assessment	Ensure the long-term climate assessment that focus on regular examination and reexamination of the climate data base are an integral part of GCOS. Up-to-date state-of-the-climate assessments should be produced.	LTA
Metadata information systems	GCOS should encourage the development of metadata information systems that provide, among other types of information, factors that may result in time dependent biases. The system should be readily accessible. It is further recommended that metadata be given high priority and that GCOS make a similar recommendation to WMO.	LTA
Overlapping measurements	Overlapping measurements of both the old and new observing systems for both in-situ and satellite data must become standard practice for critical climate variables.	LTA
Routinely assessing the quality of observations	Establish the capability for routinely assessing the quality of observations important for long-term, climate monitoring, detection, and attribution. This should include the chain of activities involved in the processing of data into useful products.	LTA
Satellite data and satellite product calibration	Better satellite data and satellite product calibration is required such as: on-board calibration for all basic measurements of radiance, including the visible channels, and more appropriate 'ground truth' measurements with the sampling and physical characteristics as comparable as possible to the satellite products.	LTA
Criticality of in situ observations	In situ measurements, including radiosonde observations, must be sustained. Their acquisition would be based on a strategy designed to provide a reasonably dense spatial and temporal distribution of observations. Radiosonde launches should be standardized and expanded in coverage. When instrument packages change, simultaneous launches of the old and new instruments, at regionally representative sites in the field, should be performed. These simultaneous launches should take place under a range of conditions, over at least one annual cycle, and at both day and night. The objective should be to determine instrument biases to a sufficient level to allow adjustments of the data for continued long-term climate monitoring.	Reconciling Temperature Observations
Ensuring the climate-monitoring effectiveness of polar orbiting satellites	NESDIS and NASA should plan launch schedules to ensure that NPP will have a minimum of one-year with both EOS and NPOESS regardless of the status of POES. Agencies should recognize that the continuity of the measurements is critical to climate science.	Reconciling Temperature Observations

NRC Category	NRC Recommendation	NRC Source (see master list below)
In situ stratospheric observations	NOAA should place a higher priority that radiosonde observations routinely reach at least the 5 hPa level. The accuracy of the data al all levels, including the stratosphere, should be well characterized, including any adjustments to the data to correct for radiation and lag errors. These improvements should be carried out for at least a designated subset of stations, if not for the entire network.	Reconciling Temperature Observations
Next generation in situ upper-air data	NOAA and other agencies should explore options for a significantly improved atmospheric sounding system, which would afford higher quality humidity observations in the global troposphere and stratosphere. Next -generation system should be implemented sooner rather than later and with adequate testing and overlap in order to establish a reliable, global, in situ sounding system.	Reconciling Temperature Observations
Radiosonde data products for monitoring global temperatures	NOAA should take responsibility for developing and updating global, radiosonde-based CDRs and for making them available to both the research community and the public. These data should include the raw soundings, as well as adjusted CDR products. The development of prompt web availability of these data, as well as general web access to metadata, should be explored.	Reconciling Temperature Observations
Radiosonde metadata	NESDIS/NCDC should work with the WMO to update and enhance existing radiosonde metadata information. This effort should not be limited to a select network but should address the entire global network. Continuing data archaeology and documentation of resulting data sets should be supported.	Reconciling Temperature Observations
Stability of radiosonde network	NOAA should attempt to minimize the number and frequency of changes in instruments and observing methods in its radiosonde and other in situ systems. Although future technologies may offer improved operational observations capabilities, a major factor in evaluating instrument changes should be the continuity of the climate record. The continuity of existing long and/or particularly high-quality or geographically-critical data records should be promoted by NOAA. Other nations should be encouraged by NOAA to follow those aspects of the U.S. observational procedures outlined in this report that help ensure high quality radiosonde-based CDRs.	Reconciling Temperature Observations
Adaptive and flexible operational system	NASA and NOAA should jointly work toward and should budget for an *adaptive* and *flexible* operational system in order to support the rapid infusion of new satellite observational technologies, the validation of new capabilities, and the implementation of new operational applications.	Transition of Research
Interagency Transition Office	A strong and effective Interagency Transition Office for the planning and coordination of activities of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) in support of transitioning research to operations should be established by and should report to the highest levels of NASA and NOAA.	Transition of Research
NASA Earth science satellite missions evaluations	All NASA Earth science satellite missions should be formally evaluated in the early stages of the mission planning process for potential applications to operations in the short, medium, or long term, and resources should be planned for and secured to support appropriate mission transition activities.	Transition of Research
Operational requirements and priorities process	NOAA and NASA should improve and formalize the process of developing and communicating operational requirements and priorities.	Transition of Research

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Acronyms

ACRIM	Active Cavity Radiometer Irradiance Monitor
AOT	Aerosol Optical Thickness
ASR	Absorbed solar radiation
ATMS	Advanced Technology Microwave Sounder
CCRI	Climate Change Research Initiative
CCSP	Climate Change Science Program
CDR	Climate Data Record
CFR	cloudiness fraction
CLASS	Comprehensive Large Array-data Stewardship System
COE	Corp of Engineers
CrIS	Cross-track Infrared Sounder
CRN	Climate Reference Network
DMSP	Defense Meteorological Satellite Program
DOC	Department of Commerce
DOD	Department of Defense
DOI	Department of Interior
EDR	Environmental Data Record
ENSO	El Niño-Southern Oscillation
EOS	Earth Observing System
EPA	Environmental Protection Agency
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
ERSST	Extended reconstruction of global sea surface temperature
FEMA	Federal Emergency Management Agency
FY	Fiscal year
GPC	Global Processing Center
GPCP	Global Precipitation Climatology Project
GVI	Global Vegetation Index
IPO	Integrated Program Office
ISCCP	International Satellite Cloud Climatology Project
JCCA	Joint Center for Climate Activities
LTA	Long-Term Archive
LWP	Liquid water path
Metop	Meteorological Operational Satellite
MJO	Madden-Julian Oscillation
MSU	Microwave Sounding Unit

NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NDVI	Normalized Density Vegetation Index
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NWS	National Weather Service
OLR	Outgoing long-wave radiation
OMPS	Ozone Mapping and Profiler Suite
ORA	Office of Research and Applications
OSDPD	Office of Satellite Data Processing
PATMOS	Pathfinder Atmosphere
POES	Polar-orbiting Operational Environmental Satellites
RDR	Raw data records
RUCL	Rutgers University Climate Laboratory
SBUV/2	Solar Backscattered Ultraviolet Radiometer/Version 2
SDS	Scientific Data Stewardship
SPC	Sector Processing Center
SSM/I	Special Sensor Microwave/Imager
SST	Sea surface temperature
USDA	United States Department of Agriculture
USGCRP	U.S. Global Change Research Program
UTH	Upper tropospheric humidity
VIIRS	Visible/Infrared Imager Radiometer Suite
WCRP	World Climate Research Programme